Aerodynamic Bicycle Wheel Design Optimisation

Rim shape design optimisation using CAESES® and TCFD®

Mattia Brenner
Head of Sales Europe
FRIENDSHIP SYSTEMS AG
brenner@friendship-systems.com

Daniel Cain
Director
Streamline Cycling
daniel.cain@streamlinecycling.co.uk

TCFD
CFD SUPPORT
info@cfdsupport.com

***CAESES®** is a software product that combines unique CAD capabilities for simulation engineers with tool automation and optimization.*

*The focus of **CAESES®** is simulation-ready geometries and the robust variation of these geometry models for faster and more comprehensive design studies and shape optimizations.*

Streamline Cycling is a company that will retail aerodynamic performance bicycle wheels and accessories in British and European markets.

All products will be developed using the latest CFD and wind tunnel testing practices.

*CFD Support introduces the new generation of CFD simulations. **TCFD®** brings an extreme increase of productivity to CFD simulations.*

***TCFD®** is unlimited in terms of users, jobs, or cores. **TCFD®** is fully automated and its beauty is that it is the user who decides how deep to dive into CFD or not at all. And all the options remain open at the same time.*

Abstract

Computational fluid dynamics (CFD) was used to optimise the shape of a racing bicycle wheel for lowest drag values at 0 degrees angle of attack. An initial validation was carried out comparing wind tunnel calculated drag and lift values for an 3D NACA 2412 aerofoil section with CFD results. A small section of rim was then optimised using **CAESES®** and **TCFD®** software where the resulting designs were validated through wind tunnel testing. **CAESES®** was used to generate and export the different wheel geometries with certain design parameters that could be optimised and for automatic postprocessing. **TCFD®** was used to run the CFD simulations within **CAESES®** and for further postprocessing purposes.

We are proud to introduce a smart and efficient wheel design optimization workflow connecting the two software packages, **CAESES®** and **TCFD®**.

Introduction

Aerodynamic performance is now one of the key factors considered when racing cyclists purchase new equipment. This is because it is now commonly known that aerodynamic drag is the main source of losses in cycling and causes between 70% to 90% of total losses in flat road races. Lateral forces felt due to a high wind yaw angles also have an impact on equipment selection with users opting for shallow wheel choices in these conditions due to the buffeting effect deeper rims can have.

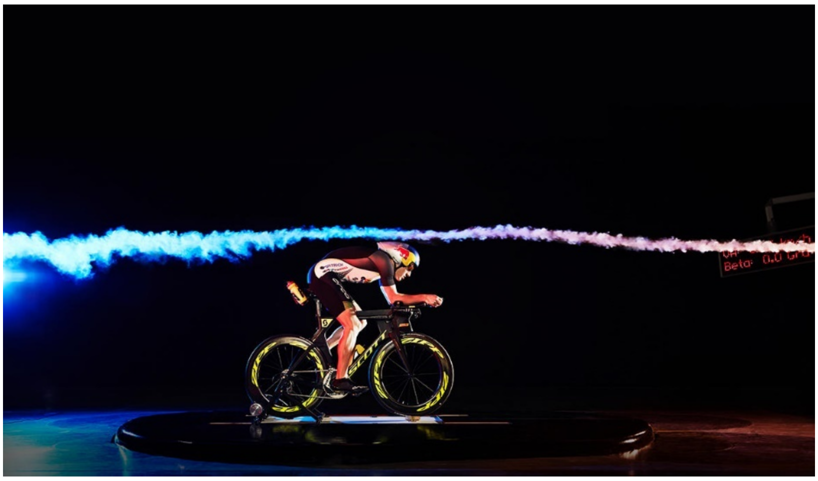


Figure 1: Optimisation of Cycling Position in a Wind Tunnel

Work carried out during reviews by Burke and Lukes et.al. into the most relevant contributions to overall performance improvements in bicycle racing discovered that the body of the cyclist is responsible for most of the aerodynamic drag, due to the large frontal area combined with relatively high drag coefficient. It is, however, necessary to also improve the aerodynamics of the bicycle's components. Work carried out by Greenwell et.al. concluded that the drag contribution from the wheels alone is on the order of 10% to 15% of the total drag and that by improving wheel design, and overall reduction in drag of more than 3% is possible. This would suggest the outcome of races can be dramatically affected by equipment choice.

This is due to the extremely small margins that decide the outcomes of races. The difference in finishing time for many races can be as low as a few seconds from a race spanning multiple hours. An example of this is the National Road Championships in Great Britain this year where 1st and 2nd place were decided by a margin of 8 seconds. (Road Cycling Results, 2019).

To date, there has been a great amount of work done to test cyclists, bikes and wheels both in the wind tunnel and through CFD, although, it is difficult to make a direct comparison between designs due to different setups for both wind tunnel and CFD tests.

Far less work has been carried out into the optimisation of rim shape for different conditions and yaw angles. The aim of this project was to investigate the aerodynamics involved in bicycle wheel design, and to optimise and design a very low drag bicycle wheel rim shape using CAESES & TCFD.

Software Use

CAESES was used for the setup of the parametric models, optimisation and viewing of the results. It is a flexible CAD modeler which enabled the creation of a fast and robust design studies for this project, with integration of TCFD simulation tools. Integrated capabilities for process automation and shape optimization made it an all-in-one design system which was used within this project. All support necessary for this project was supplied promptly by CAESES support engineers.

TCFD is an excellent CFD simulation tool by CFDSUPPORT. It's capabilities go far beyond turbomachinery CFD simulations, it can also be used for any standard CFD problem, utilising the full power of OpenFOAM combined with a very user-friendly GUI and robust solvers. This aided the design and optimisation process as most of the time was applied to solving simulations rather than the setup. TCFD also offers an extremely extensive and easy to use array of postprocessing tools which were used to diagnose key flow structures and high drag areas of the wheel. Due to the commercial nature of TCFD, it is professionally supported, well tested and has an excellent user interface. All support necessary for this project was supplied promptly by TCFD support engineers.

Aerofoil NACA 2412 Validation

An initial validation of the CFD setup was carried out using a 3D NACA 2412 aerofoil profile. This wing was tested through a range of AOAs using both CFD simulations and wind tunnel testing to validate the CFD setup that would be used for future wheel optimisations.

Geometry

The NACA profile was created using the Fusion 360 CAD software. The model had the following parameters, which can also be seen in figure 2:
Chord Length: 80mm. The reason for the slightly reduced chord length seen in figure 2b is that the end was rounded slightly to encourage better development of mesh layers in this region.
Length: 240mm
Thickness: 9.6mm
Max thickness 15% at 29.5% chord
Max camber 2% at 39.6% chord
A 3D aerofoil was used, as this could be tested both using CFD simulations and wind tunnel tests.

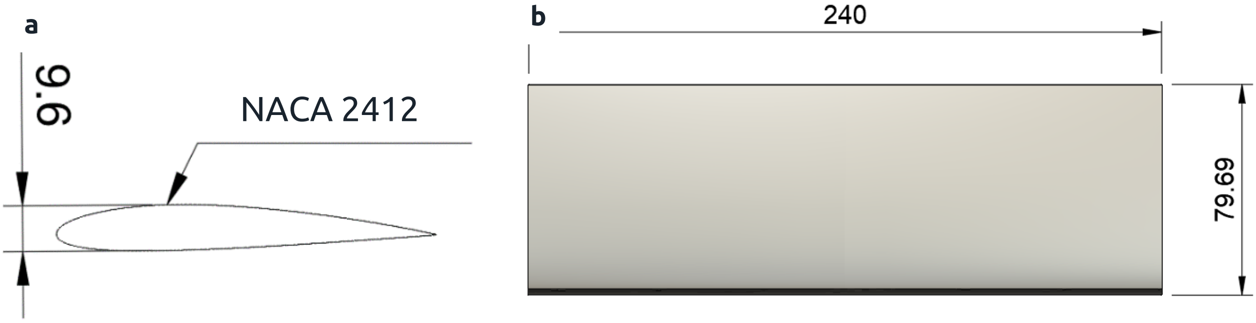


Figure 2: (a) NACA Specification Thickness (b) Specification of wing length and chord length.

CFD Setup

After the model had been generated in Fusion, it was exported as a STEP file into the CAESES working environment. The angles of attack investigated ranged from -2 to 18 degrees.
Within CAESES, the STEP file was combined with a post processing transformation to rotate the profile automatically for each simulation. This step can be seen in figure 3. From here the file was exported as an STL file which was used within the CFD processor – TCFD, for each simulation.
For each run, the 4 evaluations that took place were the Lift, Drag, Cl and Cd. Since this was just an investigation into the results at each AOA there was no objective function specified. For the Cl and Cd values the reference area came from the Length × Chord length.

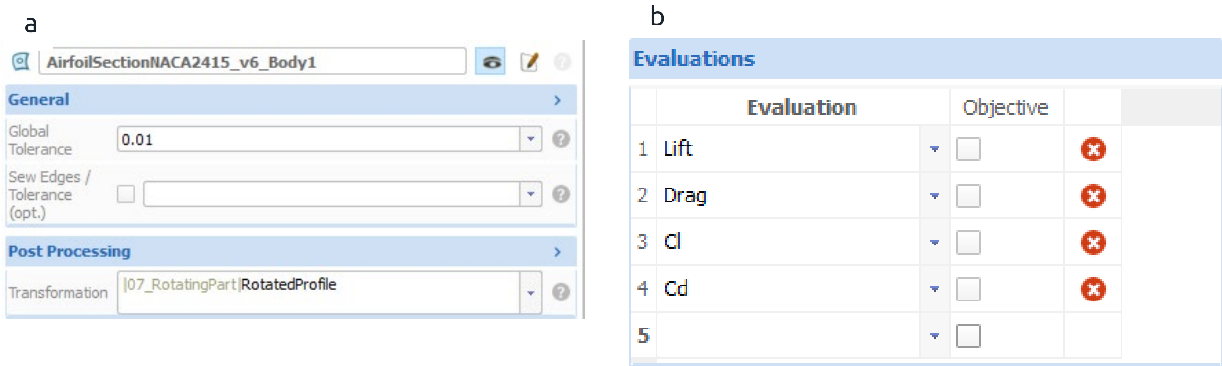


Figure 3: (a) CAESES Setup Transformation (b) Results evaluations within CAESES.

Computational Grid & Mesh

The computational grid is shown in figure 4. The grid had dimensions of 1200mm × 4000mm × 1200mm. A grid size dependency study was carried out which determined that this grid size was suitable for the verification, with a <3% variation in results coming from a larger domain.

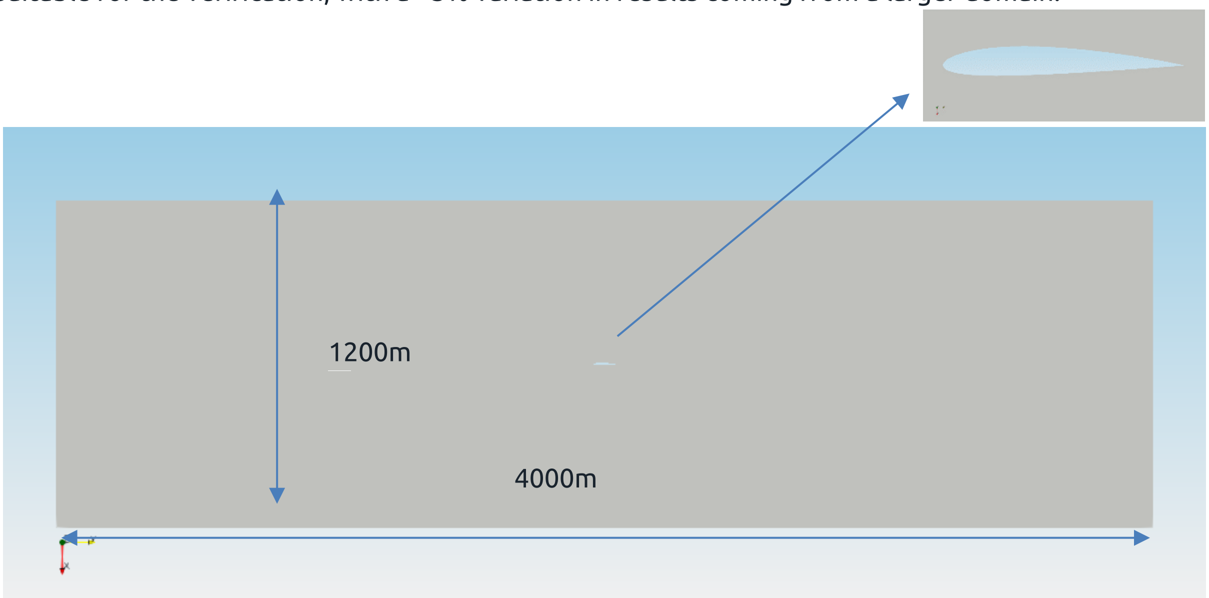


Figure 4: Top view of computation domain including main dimensions.

Figure 5: Side view of computation domain including main dimensions.

The computation grid was generated using OpenFOAMs snappyhexmesh within TCFD. 3 Refinement regions were implemented to refine the mesh toward the object under test, with boundary layers also being implemented to achieve a y+ value of 1. The total cell count for the full grid was around 3 million cells. Another sensitivity study was carried out into mesh refinement, which will be discussed in the results section.

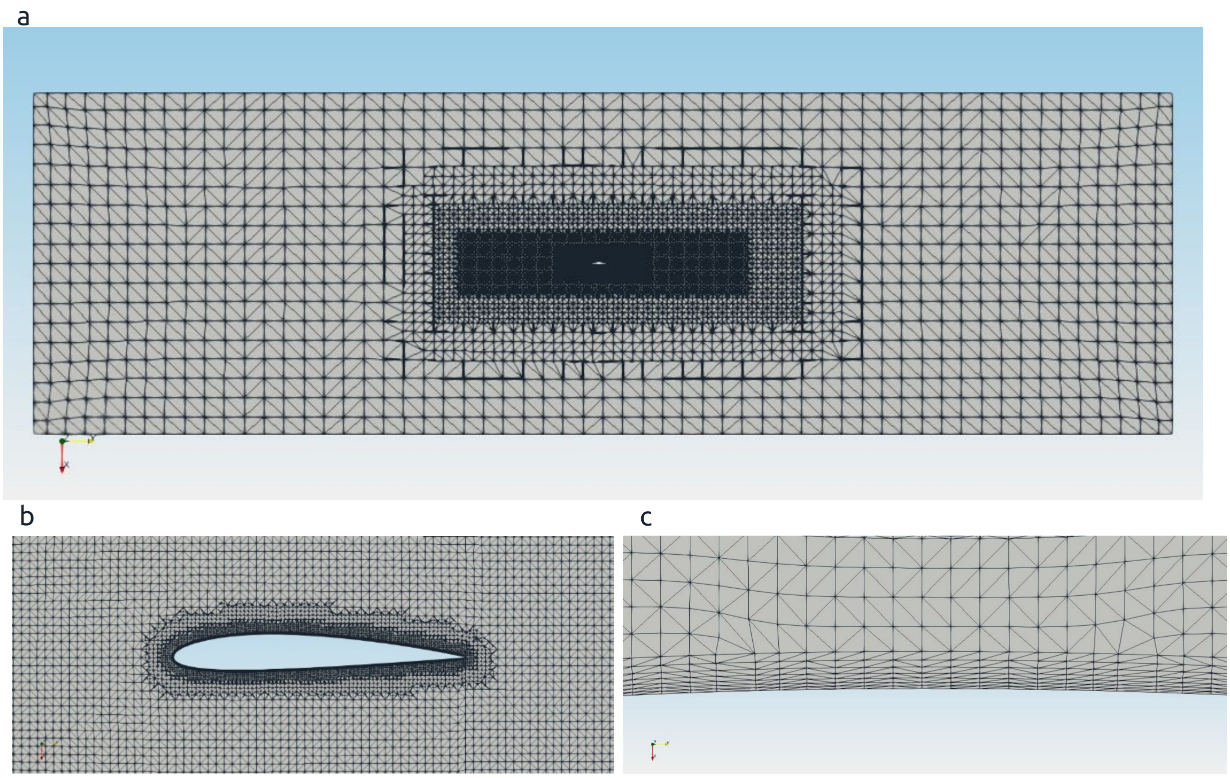


Figure 6: Volume grid slices at the centre-plane where z=0. (a) shows the full computation domain. (b) shows NACA 2412 aerofoil. (c) shows details of the boundary layers implemented.

TCFD Boundary Conditions

The boundary conditions used were the following at each respective patch:

Inlet

- Fixed free stream velocity of 9m/s or ~20mph.
- An initial turbulent energy intensity of 0.05.
- An initial turbulent dissipation rate of 100.

Outlet

- Fixed pressure outlet with a zero static gauge pressure.

Walls

- The walls surrounding the domain were modelled as wallSlip.

Aerofoil

- The aerofoil was modelled as a wall with a surface roughness assumed to be zero, which is a common simplification.

Turbulence Model

For the turbulence model, the RANS equations are solved together with the k-Omega SST turbulence model. This approach is common for aerofoil aerodynamics and shows good agreement with wind tunnel results and separation predictions. The k-Omega SST model is a two-equation eddy viscosity model that may be used for many applications involving external flows. It is a hybrid model that combines the k-Omega and k-Epsilon models. A blending function, usually referred to as F1 blends the two models together, utilising k-Omega for near wall boundary layer problems and k-Epsilon in the free stream. One drawback to this turbulence model is that it produces slightly too large turbulence levels in regions with large normal strain, such as stagnation points and regions with strong acceleration. An additional damping function F3 can be used to minimise this effect. For these simulations Low-Reynolds wall functions were used to resolve the boundary layer.
The main governing equations used within the k-Omega SST model are:

Kinematic Eddy Viscosity:

$$v_T = \frac{a_1 k}{\max\left(a_1 \omega, S F_2\right)}$$

Turbulence Kinetic Energy:

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = P_k - \beta * k\omega + \frac{\partial}{\partial x_j}\left[\left(v + \sigma_k v_T\right)\frac{\partial k}{\partial x_j}\right]$$

Specific Dissipation Rate:

$$\frac{\partial \omega}{\partial t} + U_j \frac{\partial \omega}{\partial x_j} = \alpha S^2 - \beta \omega^2 + \frac{\partial}{\partial x_j}\left[\left(v + \sigma_\omega v_T\right)\frac{\partial \omega}{\partial x_j}\right] + 2(1 - F_1)\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_i}\frac{\partial \omega}{\partial x_i}$$

Results

The following table was pulled directly from the CAESES optimisation results section. It shows the evaluated results for the NACA 2412 profile at different angles of attack (AOA).

	AOA	Lift	Drag	Cl	Cd
WindTunnelComparison_10_des0000	-2	-0.0014356368	0.0309451	-0.0015082188	0.032509601
WindTunnelComparison_10_des0001	0	0.10846221	0.031602297	0.11394577	0.033200024
WindTunnelComparison_10_des0002	2	0.21007977	0.034984403	0.22070084	0.036753121
WindTunnelComparison_10_des0003	4	0.30630738	0.042300694	0.32179346	0.044439304
WindTunnelComparison_10_des0004	6	0.41474938	0.053960011	0.435718	0.056688085
WindTunnelComparison_10_des0005	8	0.49948411	0.06725756	0.52473669	0.070657922
WindTunnelComparison_10_des0006	10	0.62165256	0.088997957	0.65308165	0.093497455
WindTunnelComparison_10_des0007	12	0.71225381	0.11115089	0.74826346	0.11677038
WindTunnelComparison_10_des0008	14	0.80574772	0.13802177	0.84648417	0.14499978
WindTunnelComparison_10_des0009	16	0.88399696	0.16887467	0.92868948	0.17741252
WindTunnelComparison_10_des0010	18	0.65221889	0.197695	0.68519333	0.20768993

Figure 6: Results table for the NACA 2412 for multiple AOA

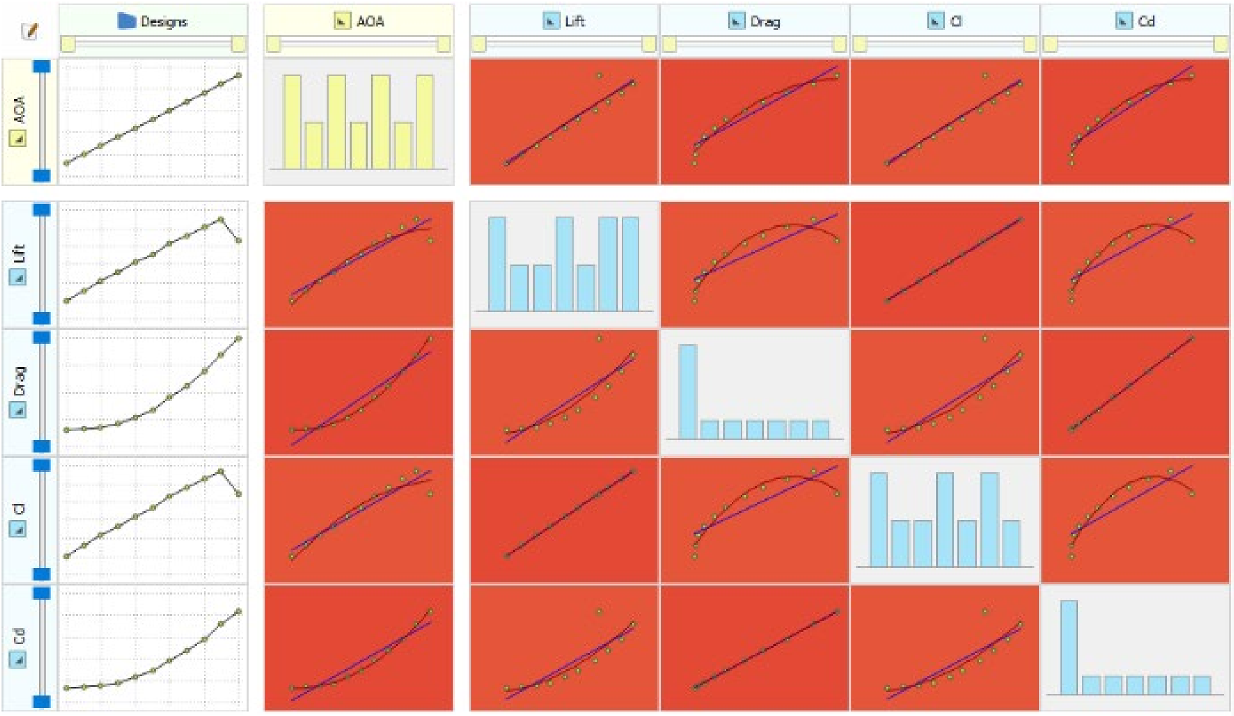


Figure 7: Results table generated for the NACA 2412 within CAESES

These figures are extremely useful in determining trends that appear in large data samples. In this situation it was used to easily plot lift(Cl) against AOA, drag(Cd) against AOA along with lift against drag. These results will be compared to wind tunnel tested values in a further section.

Postprocessing

Additional 3D pressure figure showing pressure distribution over the wing of the aerofoil.

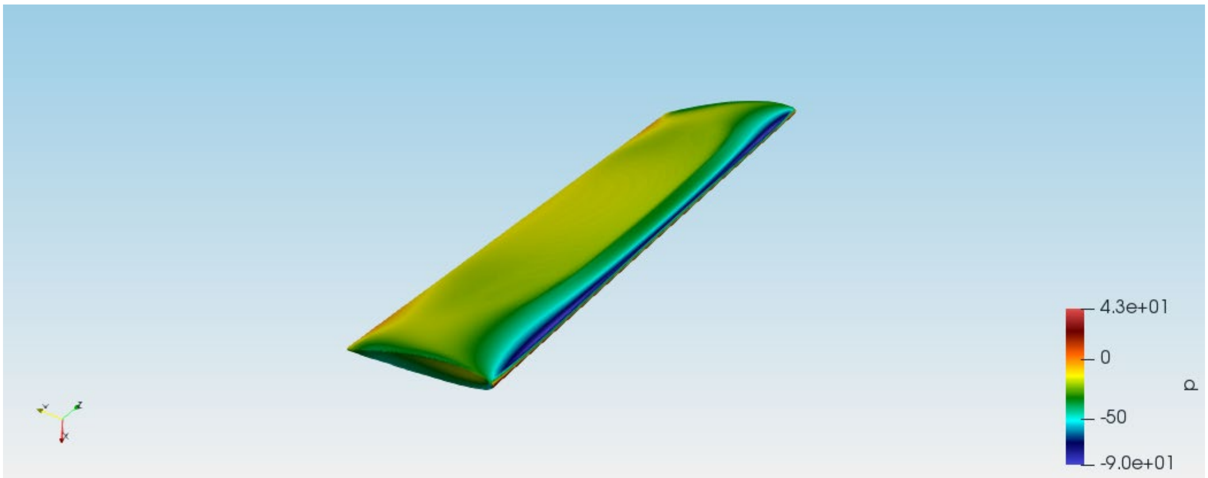


Figure 8: 3D NACA 2412 with surface pressure contours

These graphical postprocessing figures will be useful in the optimisation of the rim shape as they will determine how the flow is reacting with the external geometry of the wheel.

Wind Tunnel Testing

A small low velocity wind tunnel was manufactured to allow for the testing of small parts, aerofoils and rim sections. This allowed for a validation to be carried out on the NACA 2412 aerofoil.

Setup

The manufactured wind tunnel arrangement features a test section with dimensions detailed in the CAD drawing below.

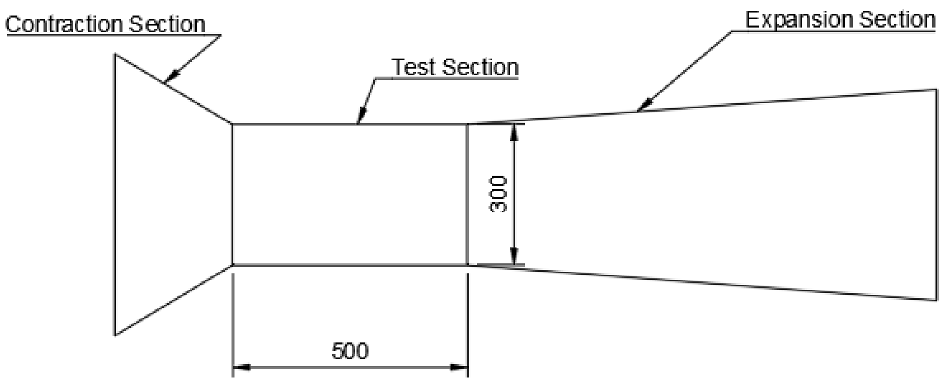


Figure 9: CAD drawing detailing the dimensions of the test section used in the wind tunnel manufacture.

Test Section

The test section geometry was 300mm × 300mm × 500mm and is shown in the picture below.

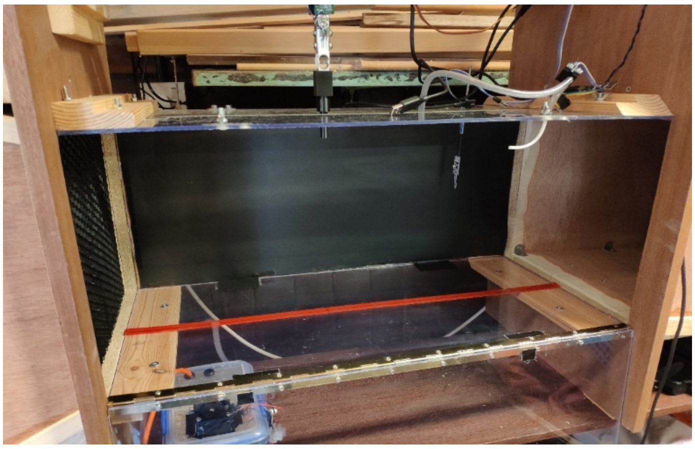


Figure 10: Test section of the wind tunnel including the force sensor and smoke generator at the bottom of the image.

Force Measurement

Force measurement was carried out using two strain gauges (1kg load sensors) mounted 90 degrees to each other. Since the force sensors rotated with the test object, the following equations were used to calculate the x force (lift) and y force (drag):

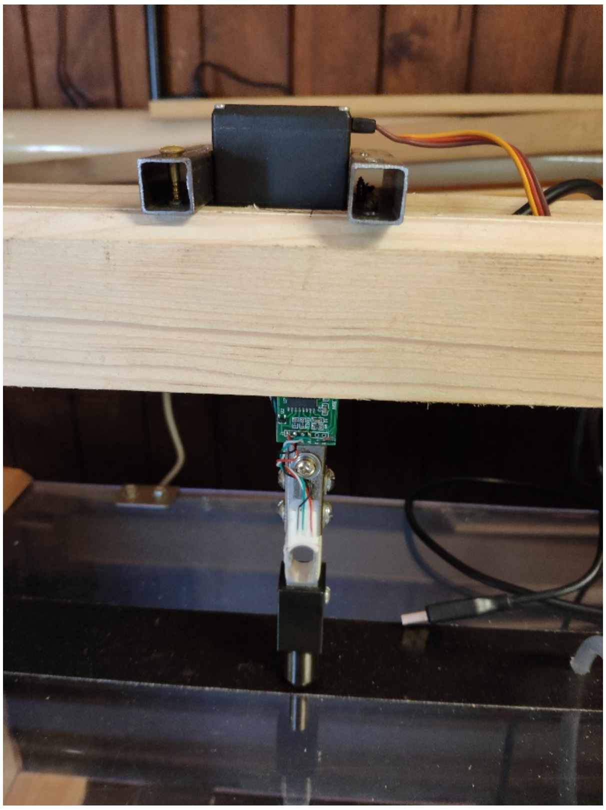


Figure 11: Force measurement setup

$$F_y = (\cos(\theta) * F_1) + (\sin(\theta) * F_2)$$
$$F_x = (\cos(\theta) * F_2) - (\sin(\theta) * F_1)$$

Where:
θ *is the angle of attack* (AOA)
F_1 *is the force inline with the EUT*
F_2 *is the force perpendicular to* F_1
F_x *is the force in the x direction* $(Lift)$
F_y *is the force in the y direction* $(Drag)$

The force sensors were mounted to a servo that was directly secured above the wind tunnel. A large bearing was used to ensure there was no play as the servo rotated. With this setup the EUT could be rotated during a test in degree intervals up to a maximum AOA of ±45 degrees. The strain gauges were connected to an Arduino, which was used to transmit the force measurements to be read and recorded on a computer. Options were utilised to allow both manual and automatic setup of the wind tunnel. The main mode used in this test allowed the automatic run of the wind tunnel at 20mph through -18 to +18 degrees in 1-degree steps every 5 seconds. The results from these experiments could quickly be collated within an Excel spreadsheet.

Wind Speed Generation

To generate the required windspeed, 9 280cfm rated computer server fans were used in an even arrangement placed at the end of the expansion section of the wind tunnel. This generated a maximum velocity of 25mph in the test section. For future experiments, different test sections of different cross-sectional area will be used to test at higher windspeeds.

EUT Setup

For each test, the aerofoil was securely attached to the force measurement setup, as can be seen in figure 12 below. Once this was in place the computer was connected to the Arduino with the windspeed and AOA being set. In the automatic setup, the AOA automatically changed after 20 readings in each position to give results for a full range of AOA. The results were recorded using the application CoolTerm. The results were then imported into Excel for ease of viewing.

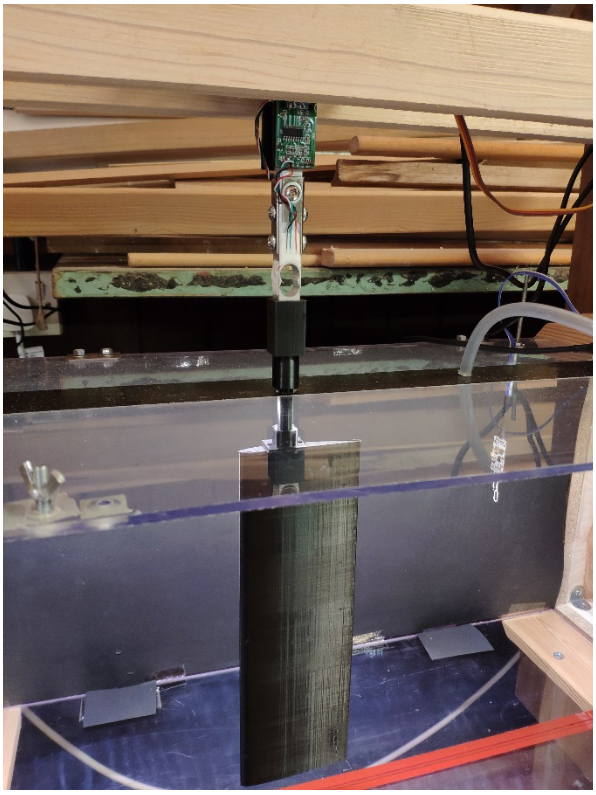


Figure 12: NACA 2412 Section attached to the force sensors.

Visual Results

Tufts were attached to both side of the aerofoil. This allowed an effect very similar to streamlines which can be used in postprocessing plots in CFD. The results are as follows.

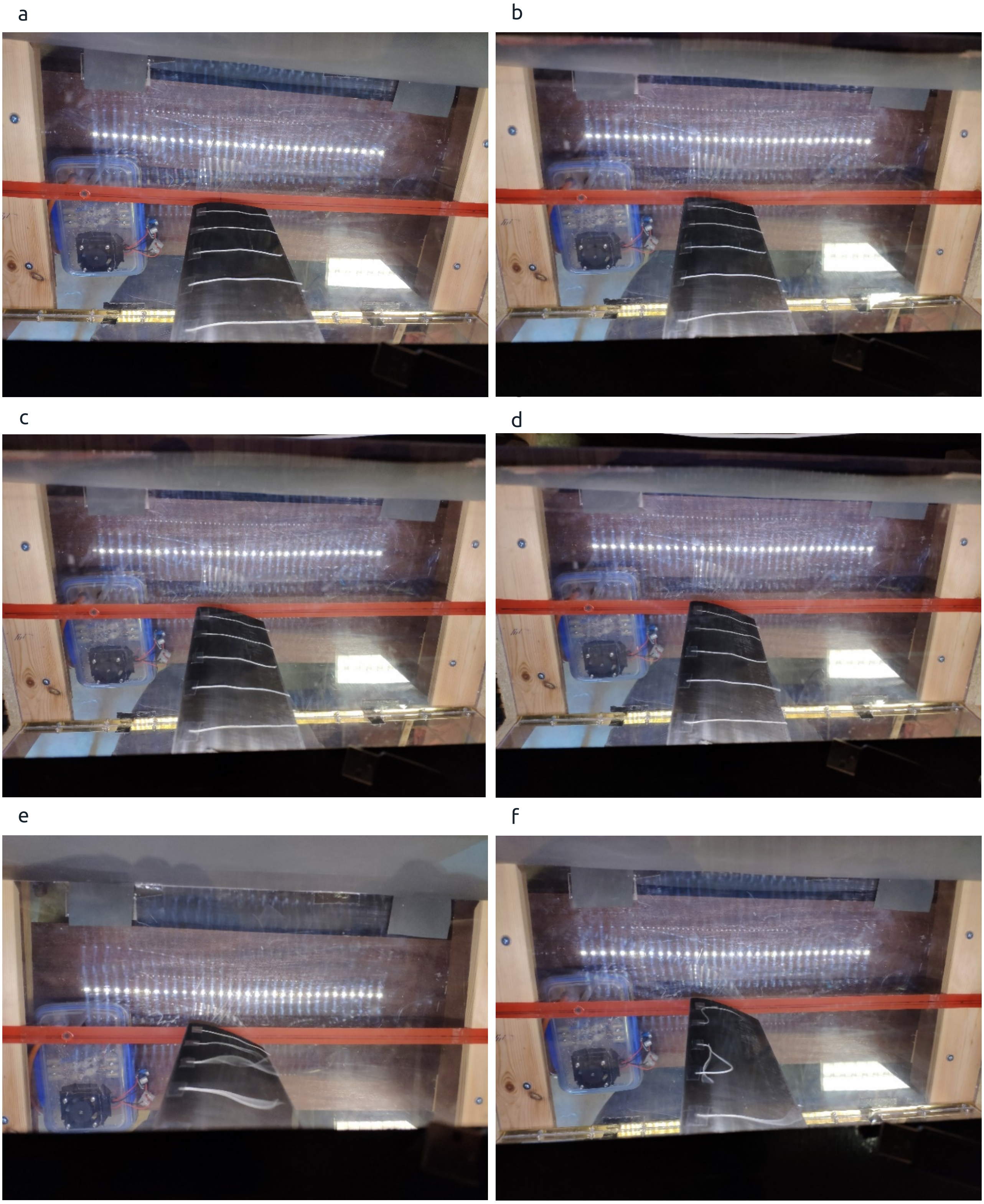


Figure 13: (a) Shows streamlines at 0 degrees (b) Shows streamlines at 4 degrees (c) Shows streamlines at 8 degrees. (d) Shows streamlines at 12 degrees (e) Shows streamlines at 15 degrees. (f) Shows streamlines at 18 degrees.

Comparison & Discussion

The results from CFD testing and wind tunnel tests were then compared giving the following tabulated results:

	Wind Tunnel vs CFD NACA 2415 Results			
	Cd - WT	Cd - CFD	Cl - WT	Cl - CFD
-2	0.032	0.033	-0.011	-0.002
0	0.030	0.033	0.130	0.114
2	0.031	0.037	0.245	0.221
4	0.034	0.044	0.357	0.322
6	0.042	0.057	0.469	0.436
8	0.053	0.071	0.566	0.525
10	0.064	0.093	0.666	0.653
12	0.083	0.117	0.744	0.748
14	0.105	0.145	0.805	0.846
16	0.174	0.177	0.700	0.929
18	0.225	0.208	0.680	0.685

These results were also plotted on a graph:

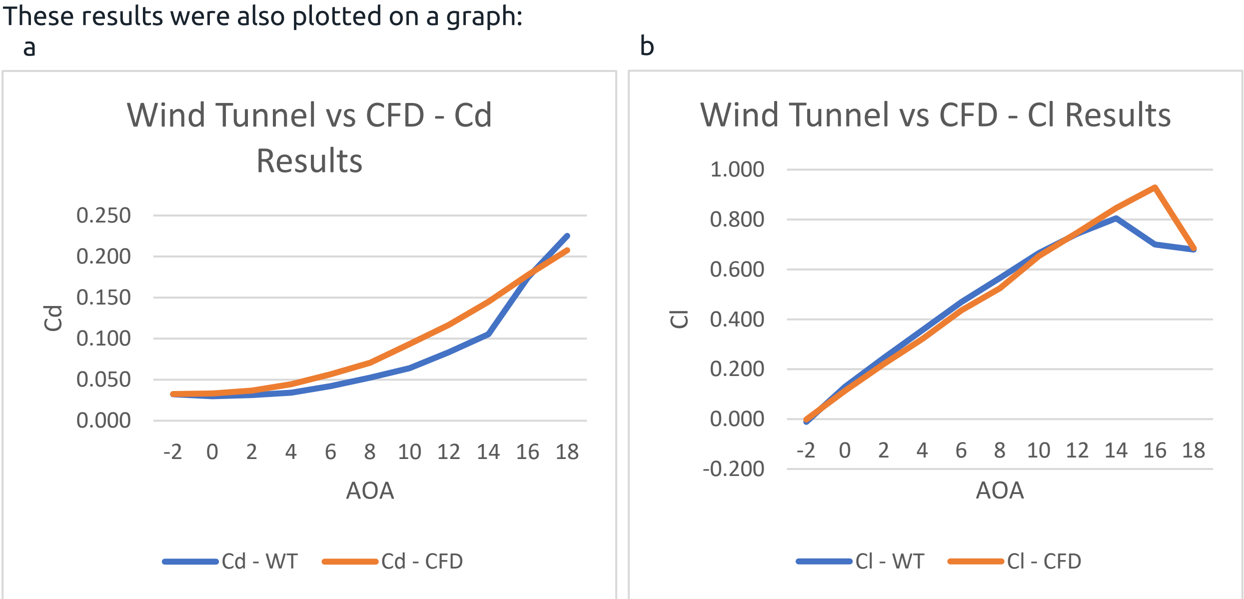


Figure 14: (a) Shows a comparison between the CFD computed results for Cd and the Wind Tunnel results. (b) Shows a comparison between the CFD computed results for Cl and the Wind Tunnel results.

These results show very good correlation with each other. The Cd values are highly mesh dependant. It was determined that using a more refined mesh would decrease the CFD calculated drag values closer to analytical results. Separation points were predicted well with the wind tunnel values showing slightly earlier separation. This could have been due to the airflow entering the test section of the tunnel being slightly turbulent.

Bicycle Rim Sections Optimisation

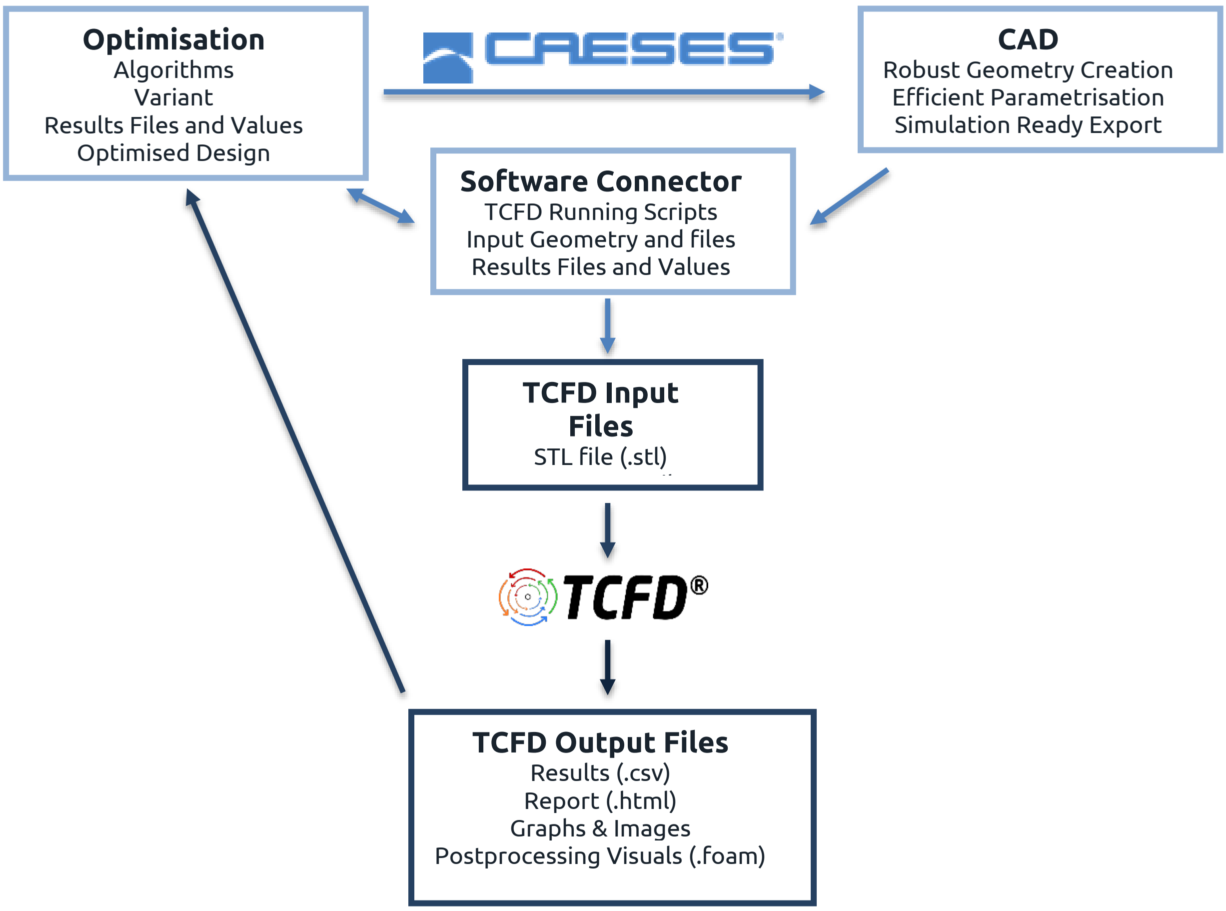
The next section of this work investigates the optimisation of a bicycle rim profile. The aim was to first determine the fastest shape at an AOA of 0 degrees and then review how this shape performs at higher AOA. This is due to fact that for high level cyclists who are likely to be using performance wheels, lower AOA were determined to be the most common (Aerodynamics, 2018). A section of the wheel was analysed both facing forward and backwards. This is due to the fact that the airflow meets the front portion of the wheel and flows over the forward-facing section, then travels to the rear of the wheel where it travels over the backwards-facing section. It was important to investigate the behaviour over both portions and optimise both. This could effectively be done using CFD and wind tunnel testing as the sections tested could fit into the manufactured wind tunnel. More emphasis was placed over the front rim section especially at low AOA as the rear section will have turbulent incoming air from the front section, hub and spokes.

Workflow Outline

CAESES® provides a CAD environment including robust and easy geometry variation, efficient parametrization and simulation-ready export. For the parametrised model, surface geometry is exported. A CFD simulation setup for the exported geometry is created in **TCFD**®. Both mesh generation and CFD simulation setup can be scripted and put into the **CAESES**® software connector.

Finally, an optimization process started in **CAESES**® and each generated geometry variant is automatically meshed and simulated with **TCFD**®.

Product Workflow



Rim Shape Parametrization - **CAESES®**

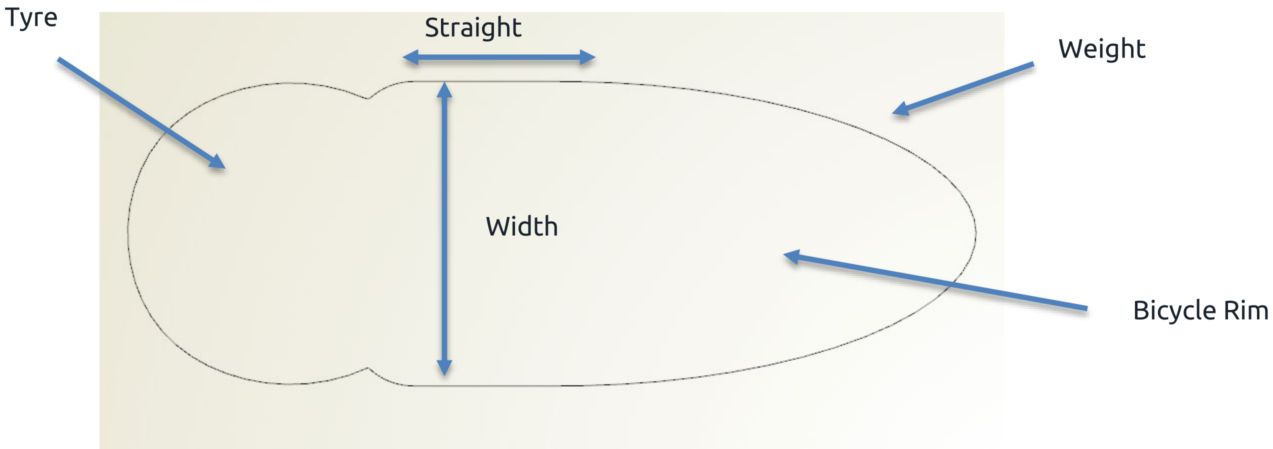
CAESES® brings along powerful capabilities for the modelling and parametrization of volutes and shapes. Any type of shape that requires optimisation, can be parametrized in a way that assures flexible and robust variation during an automated optimisation process. Fully customizable user-defined cross-sections can be used, allowing a free choice of controlling parameters. The final geometry is prepared to always and automatically provide a clean meshing domain for the downstream meshing tool, including the assignment of unique patch identifiers for the individual assignment of meshing parameters and boundary conditions.

The modelling process happens in a few steps. Firstly, the cross-section shape is defined, including all necessary shape parameters. This cross section was the revolved around 360 degrees to give the full wheel geometry. For this optimisation a 240mm section was cut out to simplify the problem.

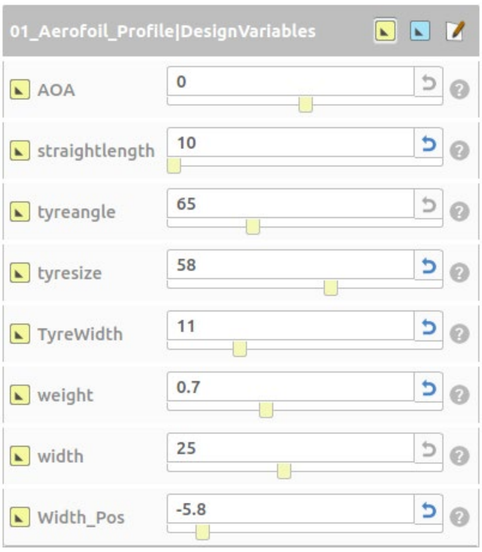
A few of the available parameters were selected for the optimisation of the rim shape and their ranges defined. These parameters were:

- Weight – This parameter is used to describe the shape of the curve. A higher number here defines a blunt curve.
- Width – This determines the width of the rim.
- Straight Length – This length is the portion of the rim which is straight before the curve begins.

An image of the parametric 2-D cross section is detailed below:



The Design Parameters within CAESES:



Some values were left unused during the optimisation. The width position (Width_Pos) and tyre parameters were kept consistent during the optimisation. As the rim was being optimised for the use of a 25mm tyre, this setup was kept constant and unchanged during optimisation. When simulating the rear portion of the wheel the AOA value was simply altered by 180 degrees to rotate the rim section.

Once revolved and cut, the final geometry used in the simulations was:

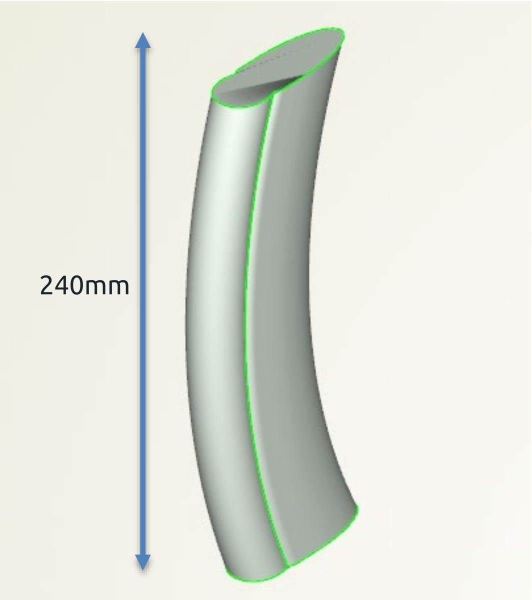


Figure 14: Rim model exported from CAESES.

CAESES Setup Files

The software connector setup within CAESES features four main sections. These being:

- Input Geometry – The final geometry is exported from CAESES in whatever required format is desired.
- Input Files – The setup files required within TCFD simulations.
- Results Values – These are the results files generated by TCFD. For the simulations, the drag and lift values were extracted and imported back to CAESES.
- Results Files – The postprocessing .foam file can be imported back into CAESES allowing the user to setup screenshots from different postprocessing fields such as pressure, velocity, turbulence intensity. These can be viewed in the design viewer for easy comparison of designs.

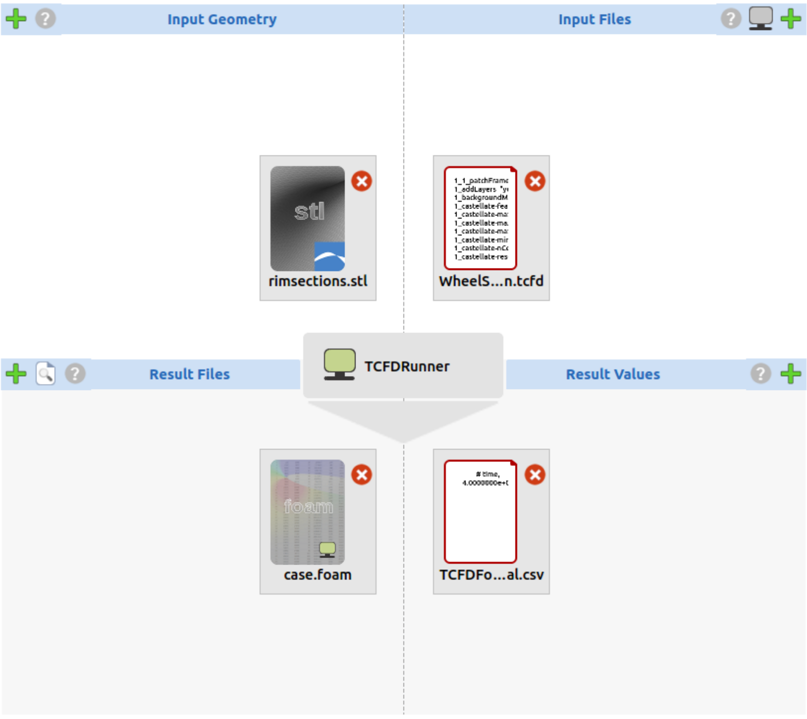


Figure 15: Setup within CAESES.

Mesh Generation - TCFD

The same grid dimensions and setup were used as the aerofoil setup. This ensure consistency between the verified setup and the rim optimisation setup. Below are images of the domain with mesh setup.

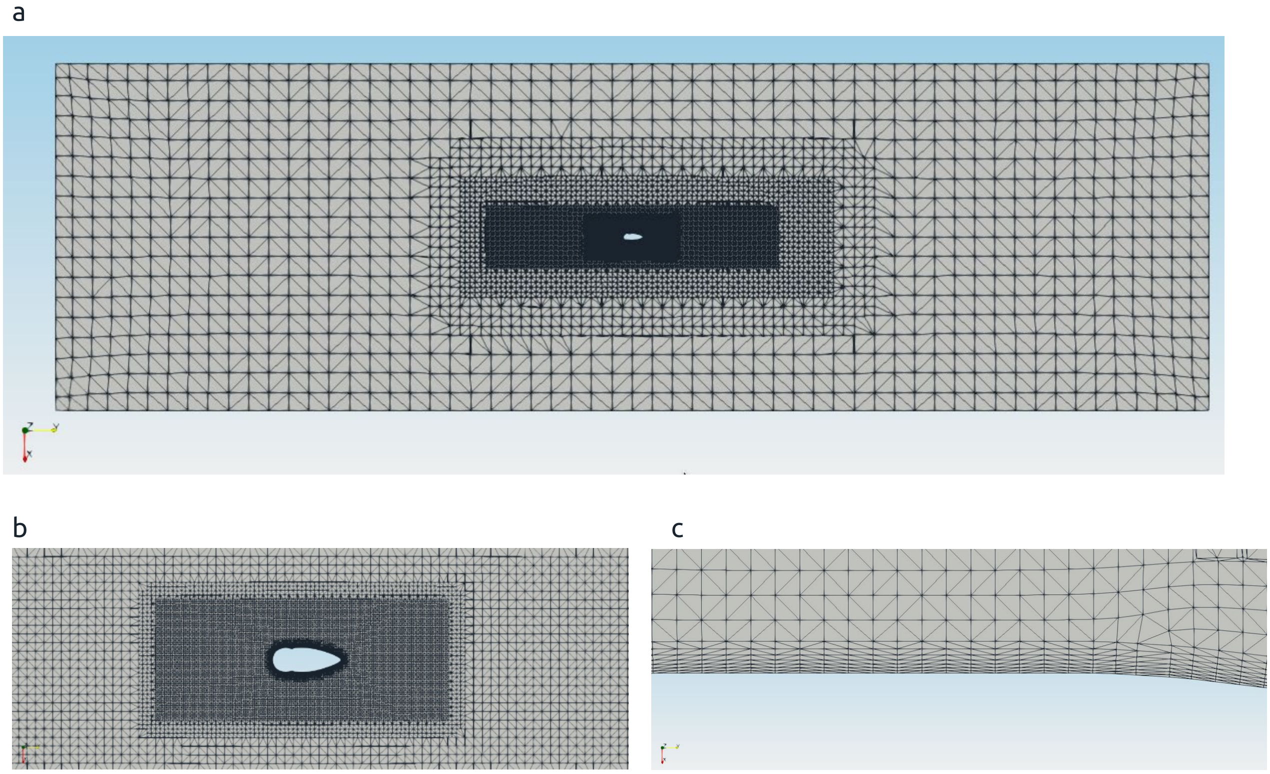


Figure 16: Shows volume grid slices at the centre-plane where z=0 (a) Overall computational domain. (b) Refinement zone with rim section. (c) Refinement layer for boundary layers.

Key Mesh Stats

- Mesh Size (cells) – 3.1Million
- Y+ Value – ~1
- Refinement zones with higher refinement levels towards the bike rim section.

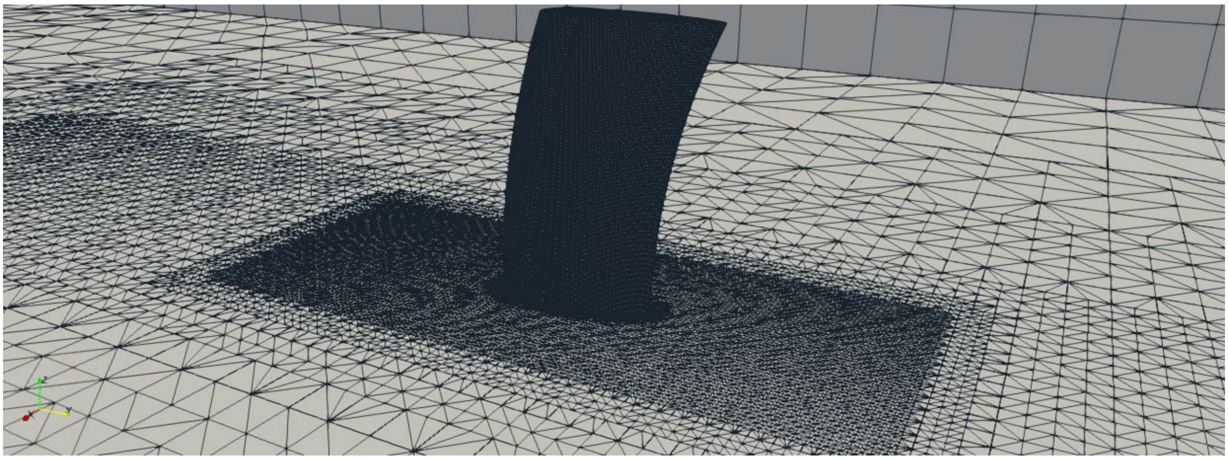


Figure 17: Shows refinement levels around the meshed rim geometry within the computational domain.

CFD Simulation - **TCFD®**

The **TCFD®** setup for this study has been set in a standard way. There is no difference between this project and any other project simulated with this tool itself. The simulation setup is created in the GUI of **TCFD®**. All the physics, boundary conditions, turbulence model, post-processing features and other CFD parameters are set in the usual way. The setup is then saved into a configuration file (*.tcfd), which is ready for incorporation into the optimization loop within CAESES. No additional operations are required.

The setup for this study contains the following flow and simulation parameters:

Solver settings

- Steady State
- Incompressible
- KOmegaSST
- Low-Re Wall Functions (y+~1)
- 2500 Iterations

Boundary Conditions at Patches

Inlet

- Fixed free stream velocity which was 9m/s or ~20mph.
- An initial turbulent energy intensity of 0.05.
- An initial turbulent dissipation rate of 100.

Outlet

- Fixed pressure outlet with a zero static gauge pressure.

Walls

- The walls surrounding the domain were modelled as wallSlip.

Rim

- The rim was modelled as a wall with a surface roughness assumed to be zero, which is a common simplification.

TCFD® automatically evaluates each simulation run and stores the results in the form of images, graphs, and CSV data files. Moreover, everything is put together in a comprehensive simulation report in HTML format. These results were then imported back into CAESES.

Optimization - **CAESES®**

CAESES® contains state-of-the-art optimization algorithms ranging from single-objective strategies for fast studies to more complex multi-objective techniques.

An optimization is a complex process. Multiple factors can constrain the extent of optimisation. First of all, one should answer several questions before designing this process: What CPU power is available? How many simulations can be performed during the project time? How many design variables can I play with for the given number of simulations? Which optimization method gives relevant results? What should be the objective function?

Let's answer some questions for this case study. We have one Intel(R) Xeon(R) CPU E5-2680 v2 CPU with 20 cores available. One design loop, including mesh generation and the **TCFD®** simulation, takes about 60 minutes. We have 3 design variables for which we performed 35 design variants, which took about 3 days to simulate. First, an exploration of the complete design space was performed using through a DoE algorithm like the Sobol or Latin Hypercube Sampling (in CAESES: Dakota > Sensitivity Analysis). That database already gives a very good indication regarding correlations, etc. Then, this first step can be followed with either a local optimization starting from a selected promising design. A reasonable number of points for sufficient coverage of a design space corresponds to N^2, where N is a number of design variables.

Finally, an objective function has to be defined. In this optimisation, the rim drag was determined to be the objective function evaluated by **TCFD®**. From the optimisation, both the front and rear portions of the rim were optimised.

Before the optimization process, we simulated the original design for both the front portion and rear.

Front:

	AOA	straightlength	weight	width	resultantforcedragnewtons
DesignAssembler01_22_des0000	0	18	0.7	25	0.1018341

Rear:

	AOA	weight	width	straightlength	resultantforcedragnewtons
DesignAssembler01_18_des0000	0	0.7	25	18	0.11698173

After 40 simulations we get the best design listed in the table below.

Front

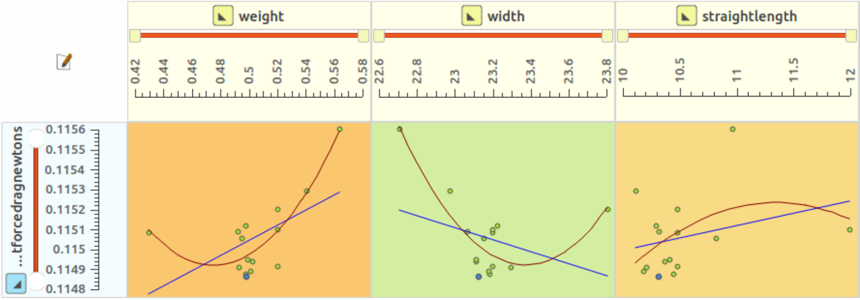
	weight	width	straightlength	AOA	resultantforcedragnewtons
Dakota_23_des0014	0.29595618	24.701692	10	0	0.087770932
Dakota_23_des0011	0.30910035	24.823435	10	0	0.088153274
Dakota_23_des0008	0.34602944	24.652004	10	0	0.088166608
Dakota_23_des0013	0.30910035	24.823435	10.1875	0	0.088231384
Dakota_23_des0010	0.36832028	24.635916	10.03138	0	0.088484899
Dakota_23_des0012	0.32114998	24.950112	10	0	0.088578315

Rear

	weight	width	straightlength	AOA	resultantforcedragnewtons
Dakota_19_des0012	0.49803153	23.128201	10.321688	0	0.11486603
Dakota_19_des0007	0.49772288	23.182313	10.451416	0	0.11488363
Dakota_19_des0015	0.50107085	23.175607	10.18551	0	0.11489618
Dakota_19_des0011	0.49317243	23.293025	10.210033	0	0.11491492
Dakota_19_des0002	0.52	23.2	10.48	0	0.11492141
Dakota_19_des0014	0.50216246	23.111138	10.368902	0	0.11494192

The reason for the difficulty in reducing the drag on the rear part of the wheel is that the tyre is on the aft of the model. Further work into surface features on the tyre, such as dimples, may reduce the drag further.

CAESES® provides a nice visualization tool for a sensitivity analysis. The user can follow a table of graphs showing which parameters affect the objective function and read possible dependencies, which are depicted by linear or quadratic interpolation:



From the results, a varient was chosen which was the best balance between the optimisations from the front and the rear. The final varient was:

Front

	weight	width	straightlength	AOA	resultantforcedragnewtons
Dakota_14_des0020	0.43253656	23.202516	10.481856	0	0.089781919

Rear

	weight	width	straightlength	AOA	resultantforcedragnewtons
Dakota_16_des0020	0.43253656	23.202516	10.481856	0	0.11492756

The optimization process reduced the drag value by **13%** on the front portion of the rim and **2%** on the rear portion of the rim when compared to the base design. The final outcome of this study is summarised in the table below:

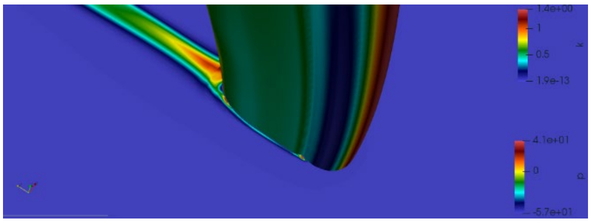
	Weight	Width	Straight Length	Drag Force	% Reduction
Front Base Design	0.7	25	18	0.101834	
Front Optimised Design	0.4325	23.2	10.48	0.8978	13%
Rear Base Design	0.7	25	18	0.11698	
Rear Optimised Design	0.4325	23.2	10.48	0.1149	2%

This difference can be visualised in the following postprocessing images which show turbulence around the rim.

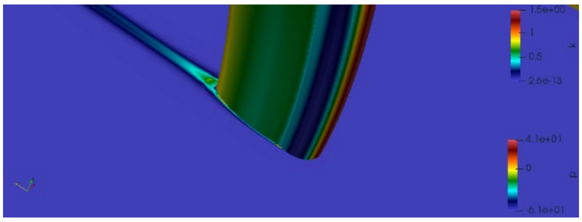
Benchmark **Optimised**

Front

a

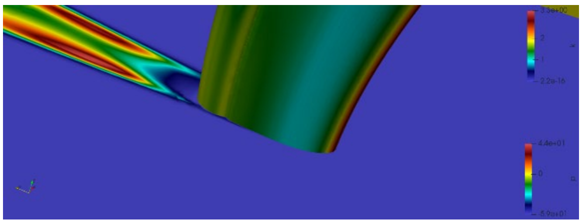


b



Rear

c



d

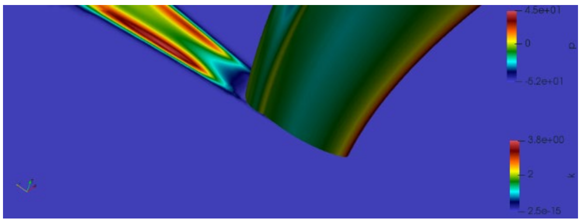


Figure 18: Shows Turbulence Intensity at the z=0 plane with pressure distribution over the rim section (a) Baseline front facing section. (b) Optimised Front facing rim. (c) Baseline rear facing rim. (d) Optimised rear facing rim.

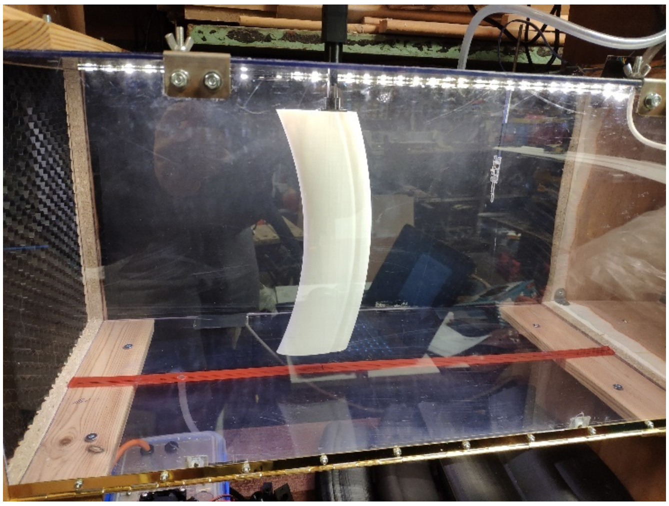
Wind Tunnel

Setup

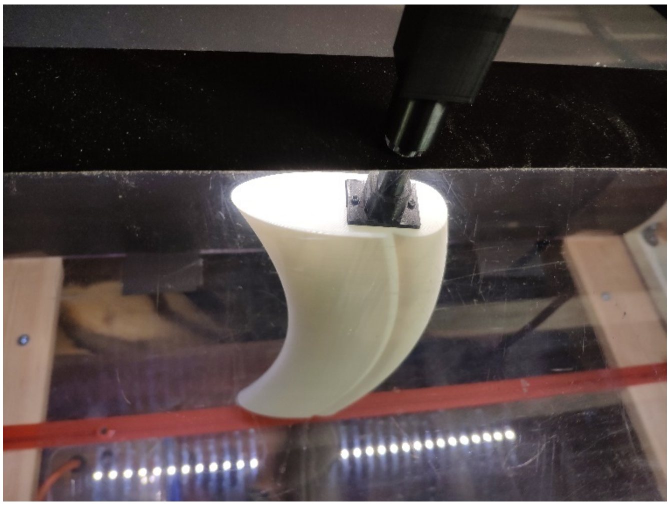
The setup was the same as the aerofoil verification. The model was capable of being attached both facing forwards and backwards to allow the front and rear sections to be tested. Several models were tested, each given a code such as 250710. In this code the first two digits are the model width, the second two are the curve (Weight) and the last two are the Straight length.

All models were tested from -16 degrees to 22 degrees. This allowed investigation into not only the models at low yaw AOA but also stall angles.

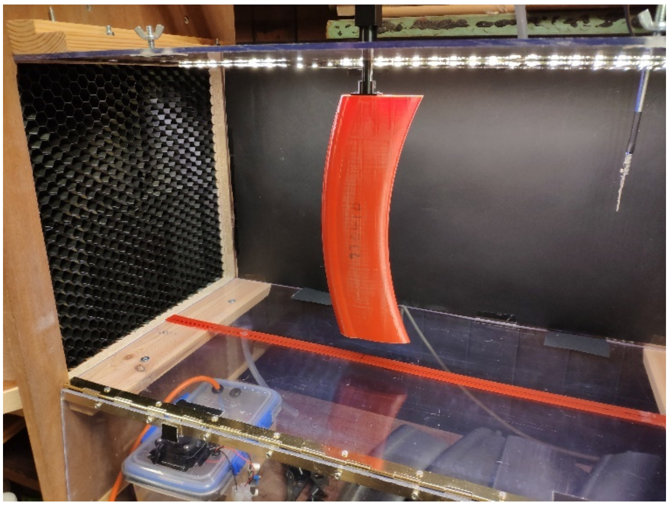
a



b



c



d

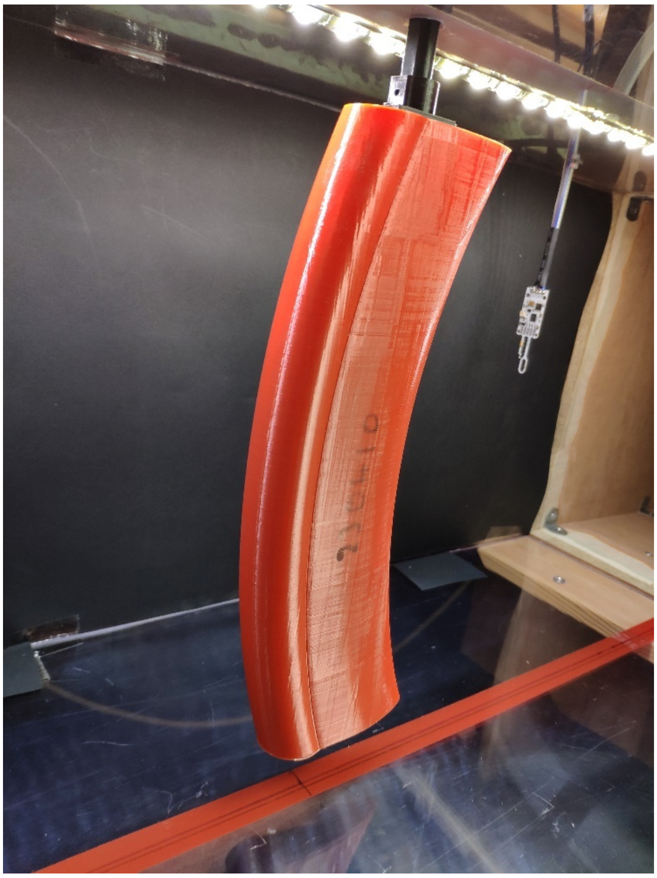


Figure 19: (a)(b) Shows rear facing 3d printed rim design in wind tunnel.

(c)(d) Shows forward facing 3d printed rim design in wind tunnel.

Results

For the rim sections tested the tabulated results were:

	250718						230410					
	FRONT		BACK		COMBINED		FRONT		BACK		COMBINED	
AOA	DRAG	SIDE	DRAG	SIDE	DRAG	SIDE	DRAG	SIDE	DRAG	SIDE	DRAG	SIDE
-16	204	256	300	140	504	396	201	177	273	552	474	729
-15	204	256	286	388	490	644	200	145	255	606	455	751
-14	204	256	276	448	480	704	197	134	104	632	301	766
-13	199	259	258	477	457	736	195	110	53	638	248	748
-12	193	257	61	497	254	754	191	103	36	636	227	739
-11	185	242	58	515	243	757	187	81	30	612	217	693
-10	174	234	63	519	237	753	179	30	36	584	215	614
-9	151	213	64	523	215	736	175	16	47	547	222	563
-8	62	474	60	486	122	960	173	2	59	510	232	512
-7	68	434	65	449	133	883	159	-46	71	462	230	416
-6	71	398	78	391	149	789	72	207	84	421	156	628
-5	74	343	88	350	162	693	69	199	97	339	166	538
-4	79	275	90	312	169	587	68	179	103	296	171	475
-3	83	229	100	276	183	505	71	156	108	233	179	389
-2	85	180	101	223	186	403	72	124	113	193	185	317
-1	88	122	107	178	195	300	74	92	119	117	193	209
0	91	80	111	103	202	183	74	63	124	50	198	113
1	91	10	114	34	205	44	73	29	126	16	199	45
2	92	-60	113	-25	205	-85	75	-17	121	-24	196	-41
3	90	-121	110	-108	200	-229	74	-40	120	-66	194	-106
4	89	-163	102	-175	191	-338	74	-67	119	-132	193	-199
5	88	-207	102	-232	190	-439	73	-106	110	-204	183	-310
6	85	-259	95	-289	180	-548	73	-142	104	-267	177	-409
7	80	-331	90	-349	170	-680	73	-166	100	-334	173	-500
8	76	-374	82	-392	158	-766	72	-197	89	-391	161	-588
9	71	-437	72	-458	143	-895	80	-174	78	-458	158	-632
10	68	-466	62	-504	130	-970	161	61	65	-501	226	-440
11	69	-490	54	-548	123	-1038	174	29	46	-554	220	-525
12	175	-201	39	-606	214	-807	184	1	37	-594	221	-593
13	183	-233	24	-656	207	-889	186	-51	21	-629	207	-680
14	193	-248	9	-698	202	-946	187	-70	10	-670	197	-740
15	198	-219	-1	-720	197	-939	193	-50	0	-691	193	-741
16	201	-239	-16	-777	185	-1016	196	-72	-17	-735	179	-807
17	207	-227	-33	-805	174	-1032	199	-112	-28	-760	171	-872
18	209	-270	-54	-851	155	-1121	201	-128	-39	-790	162	-918
19	209	-270	-64	-876	145	-1146	201	-158	-51	-814	150	-972
20	209	-270	-79	-905	130	-1175	203	-163	-62	-836	141	-999
21	209	-270	-101	-949	108	-1219	203	-177	-70	-852	133	-1029
22	209	-270	-116	-974	93	-1244	206	-202	-60	-838	146	-1040

	251110						270710						250710					
	FRONT		BACK		COMBINED		FRONT		BACK		COMBINED		FRONT		BACK		COMBINED	
AOA	DRAG	SIDE	DRAG	SIDE	DRAG	SIDE	DRAG	SIDE	DRAG	SIDE	DRAG	SIDE	DRAG	SIDE	DRAG	SIDE	DRAG	SIDE
-16	205	264	-47	804	158	1068	211	241	16	733	227	974	203	245	-17	763	186	1008
-15	203	249	-35	771	168	1020	206	235	-35	780	171	1015	199	215	-32	760	167	975
-14	200	264	-23	747	177	1011	203	222	-27	745	176	967	198	238	-21	726	177	964
-13	195	222	-6	701	189	923	190	233	-12	712	178	945	192	195	-10	698	182	893
-12	183	269	4	660	187	929	185	245	-4	690	181	935	191	216	4	658	195	874
-11	176	284	18	617	194	901	169	220	9	644	178	864	183	215	17	623	200	838
-10	152	246	38	546	190	792	37	556	30	581	67	1137	169	196	35	563	204	759
-9	150	237	49	511	199	748	43	550	38	555	81	1105	156	159	42	531	198	690
-8	59	464	55	479	114	943	51	506	47	525	98	1031	54	429	52	502	106	931
-7	63	422	68	420	131	842	58	466	57	476	115	942	55	401	65	451	120	852
-6	67	387	77	386	144	773	63	428	67	446	130	874	60	357	72	419	132	776
-5	72	332	80	353	152	685	69	384	73	397	142	781	67	292	79	377	146	669
-4	74	301	92	313	166	614	74	322	84	348	158	670	67	263	90	323	157	586
-3	80	236	96	260	176	496	79	258	97	297	176	555	72	207	98	247	170	454
-2	84	174	102	222	186	396	81	215	106	243	187	458	74	155	106	192	180	347
-1	87	128	104	178	191	306	82	158	114	185	196	343	78	95	110	135	188	230
0	87	77	108	134	195	211	82	100	118	118	200	218	79	68	113	81	192	149
1	89	11	113	50	202	61	82	66	120	60	202	126	79	19	115	14	194	33
2	90	-49	113	-23	203	-72	81	6	122	4	203	10	79	-19	119	-49	198	-68
3	88	-92	109	-109	197	-201	82	-41	122	-84	204	-125	79	-95	114	-79	193	-174
4	88	-153	102	-197	190	-350	81	-98	118	-138	199	-236	77	-135	112	-139	189	-274
5	85	-204	102	-237	187	-441	82	-150	111	-208	193	-358	76	-186	106	-205	182	-391
6	81	-270	96	-287	177	-557	78	-234	100	-273	178	-507	74	-237	99	-294	173	-531
7	79	-317	90	-339	169	-656	73	-285	93	-323	166	-608	72	-300	84	-383	156	-683
8	72	-372	81	-390	153	-762	70	-344	82	-374	152	-718	67	-354	80	-414	147	-768
9	66	-443	68	-454	134	-897	64	-405	62	-449	126	-854	64	-391	69	-474	133	-865
10	61	-482	62	-486	123	-968	55	-455	55	-477	110	-932	60	-446	55	-523	115	-969
11	57	-515	53	-527	110	-1042	44	-507	43	-522	87	-1029	62	-442	47	-556	109	-998
12	161	-244	36	-587	197	-831	36	-541	30	-568	66	-1109	177	-150	33	-604	210	-754
13	183	-233	21	-632	204	-865	29	-563	16	-613	45	-1176	180	-152	22	-632	202	-784
14	187	-227	7	-687	194	-914	22	-591	1	-645	23	-1236	188	-180	6	-680	194	-860
15	196	-293	-4	-719	192	-1012	180	-215	-10	-676	170	-891	196	-181	-4	-717	192	-898
16	198	-244	-18	-759	180	-1003	186	-232	-27	-724	159	-956	198	-208	-26	-769	172	-977
17	205	-297	-27	-789	178	-1086	194	-221	-36	-748	158	-969	204	-208	-35	-791	169	-999
18	209	-271	-41	-824	168	-1095	201	-215	-51	-787	150	-1002	206	-228	-49	-822	157	-1050
19	207	-267	164	-470	371	-737	204	-235	-68	-823	136	-1058	208	-216	-68	-870	140	-1086
20	207	-267	173	-482	380	-749	205	-224	-79	-846	126	-1070	209	-242	-81	-900	128	-1142
21	207	-267	179	-482	386	-749	205	-224	-96	-875	109	-1099	208	-236	-97	-926	111	-1162
22	207	-267	185	-507	392	-774	205	-224	-115	-907	90	-1131	208	-236	-111	-945	97	-1181

These results were also graphed:

Front

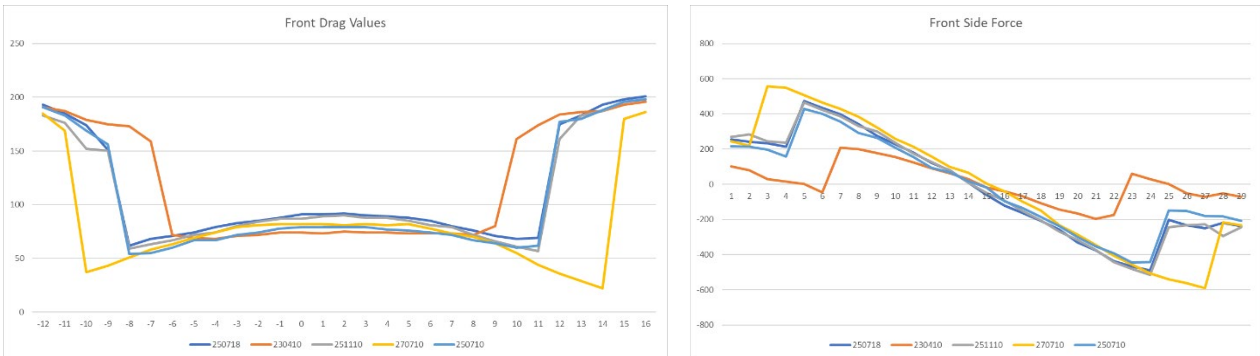


Figure 20: (a) Shows drag on the front facing wheel sections(b) Shows side force on the front facing 3d printed rim design.

Rear

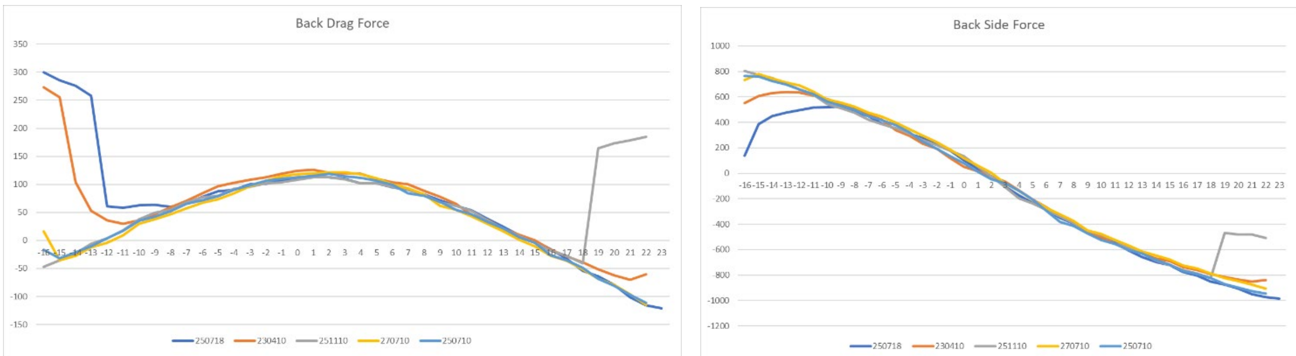


Figure 21: (a) Shows drag on the rear facing wheel sections(b) Shows side force on the rear facing 3d printed rim design.

Combined

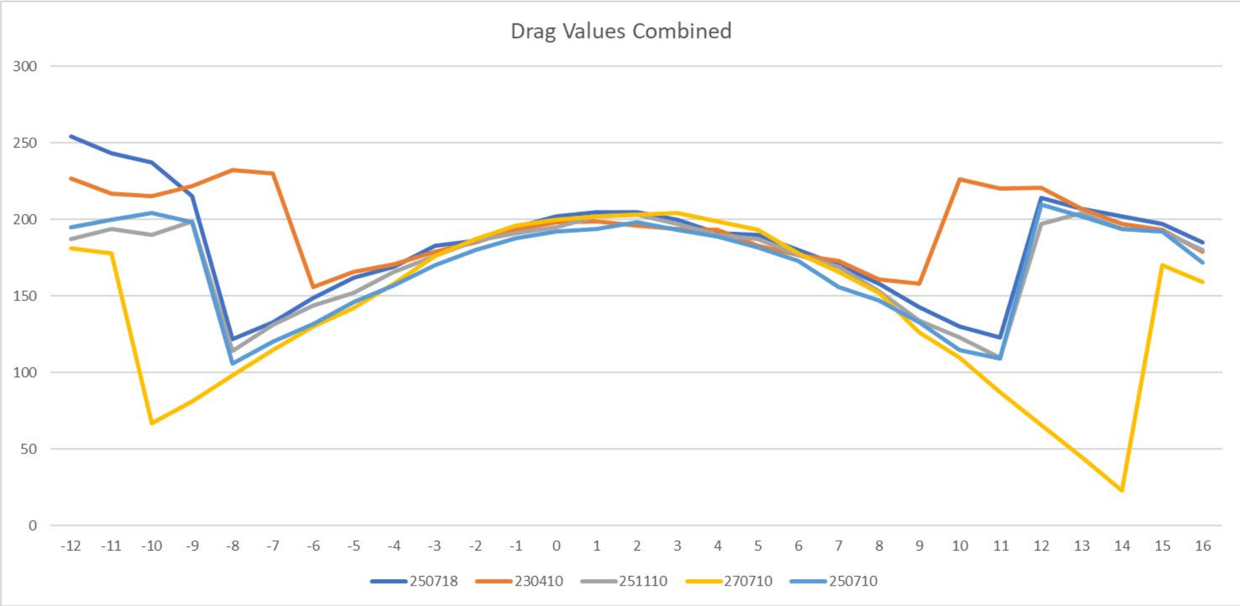


Figure 22: Shows drag on the combined wheel sections.

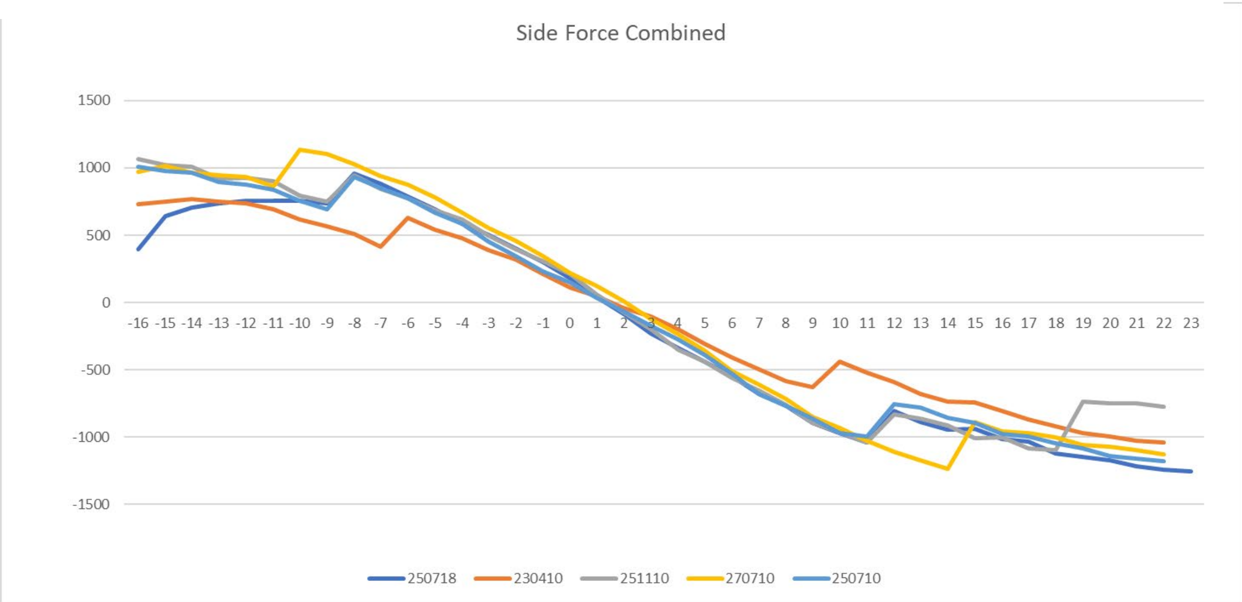


Figure 23: Shows side force on the combined wheel sections.

Discussion

From these results, the following trends were noticed. Firstly, the design optimised through CAESES and TCFD was the lowest drag shape for the front section through AOA up to 6 degrees. This shape however stalls thereafter. For cyclist averaging very high speeds ~30mph, this shape would be ideal. Due to the importance of the front portion, this shape would provide the lowest drag in most situations, as the rear section has less weighting on overall drag because it is in the wake of the front portion at low AOA.
It was also noticed that the wider rim section performed much better at higher angles of attack. This width would therefore be suitable for club riders or those who average <20mph. However, due to the increased frontal area this rim was slower however at lower AOA.

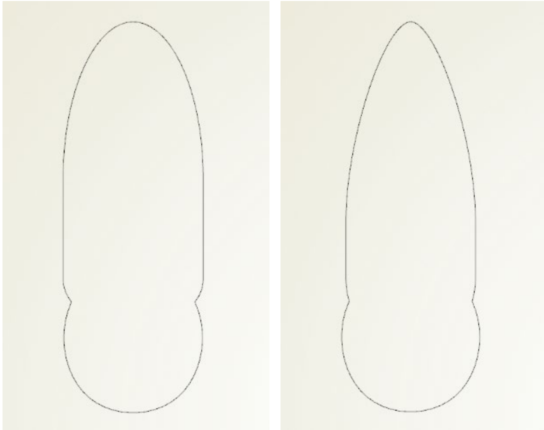
Future work can be carried out to determine the fastest rim geometry at higher AOA.

The drag values calculated from the CFD solver matched the wind tunnel values closely, which gives extra confidence for using this optimisation process to develop fast bicycle rim shapes.

Conclusion

A comparison of the base and optimized designs is shown in the figures on the right. The base design can be seen on the left with the optimised design being on the right.

In a short period of time, the bicycle rim geometry was optimized to achieve low drag values. Altogether, **40 simulations** were performed for both the front and rear sections to obtain an optimized design.



As a result, the drag values were reduced by 13% and compared very well with wind tunnel received results.

Each simulated design has its own **TCFD®** report, from which all the important flow parameters can be read. Additionally, custom visualizations can be pre-set and rendered for each design. There is almost no limitation and the user can easily create any template for custom rendering.

This study clearly shows synergy between **CAESES®** and **TCFD®**. This combination brings the engineers smooth and modern CAE tools to make their engineering more efficient. **CAESES®** gives you unlimited access to geometry modelling, variation, and optimization. **TCFD®** brings an unlimited and accurate CFD power with no additional costs in terms of a number of users, jobs or cores. The available hardware resources can be used at 100%, without any restrictions. This process is automated and can be tailored to other CFD cases. Therefore, it is suitable not only for highly-skilled engineers, but for all engineers from diverse industries.

FRIENDSHIP SYSTEMS

www.caeses.com
+49-331-96766-0
sales@friendship-systems.com

www.streamlinecycling.co.uk
+447925 375 133
daniel.cain@streamlinecycling.co.uk

CFDsupport

www.cfdsupport.com
+420 212 243 883
info@cfdsupport.com