The HUNT Aerodynamicist Wheel Development

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1.0 <u>Purpose of the wheels</u>

Aerodynamicist Road Wheels: A range engineered for varying terrains of competitive road racing, that must deliver performance equal to or better than key leading competitors. ETRTO compatible with tubeless and non-tubeless 25mm-50mm tyres, aero optimized for today's most popular road tyre width 28mm.

2.0 <u>Outline of the Process</u>

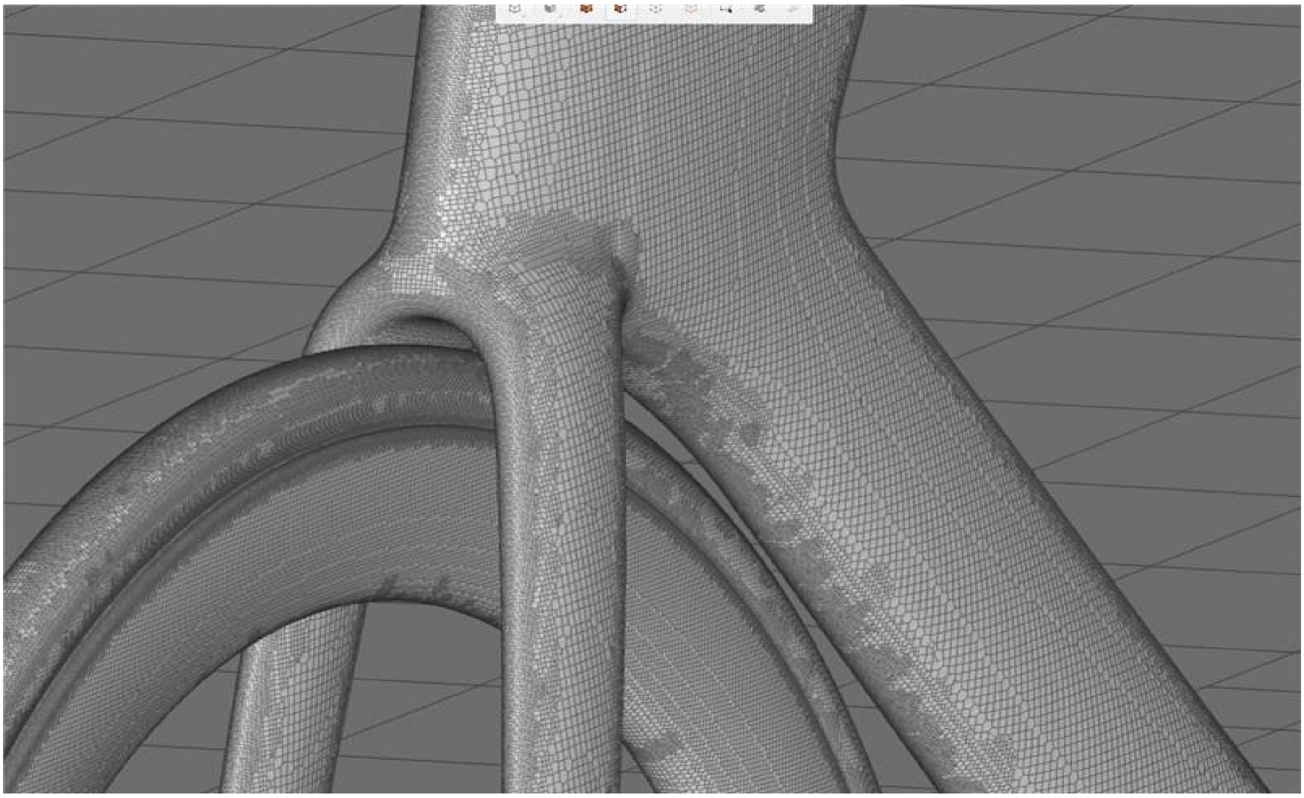
Working within the constraints of the product brief, the engineering team at Hunt began a series of Computational Fluid Dynamics (CFD) simulations to develop the most aerodynamic profiles for both front and rear rims. In addition, a number of competitor wheels from Roval, Enve and Zipp were laser scanned and simulated in CFD.

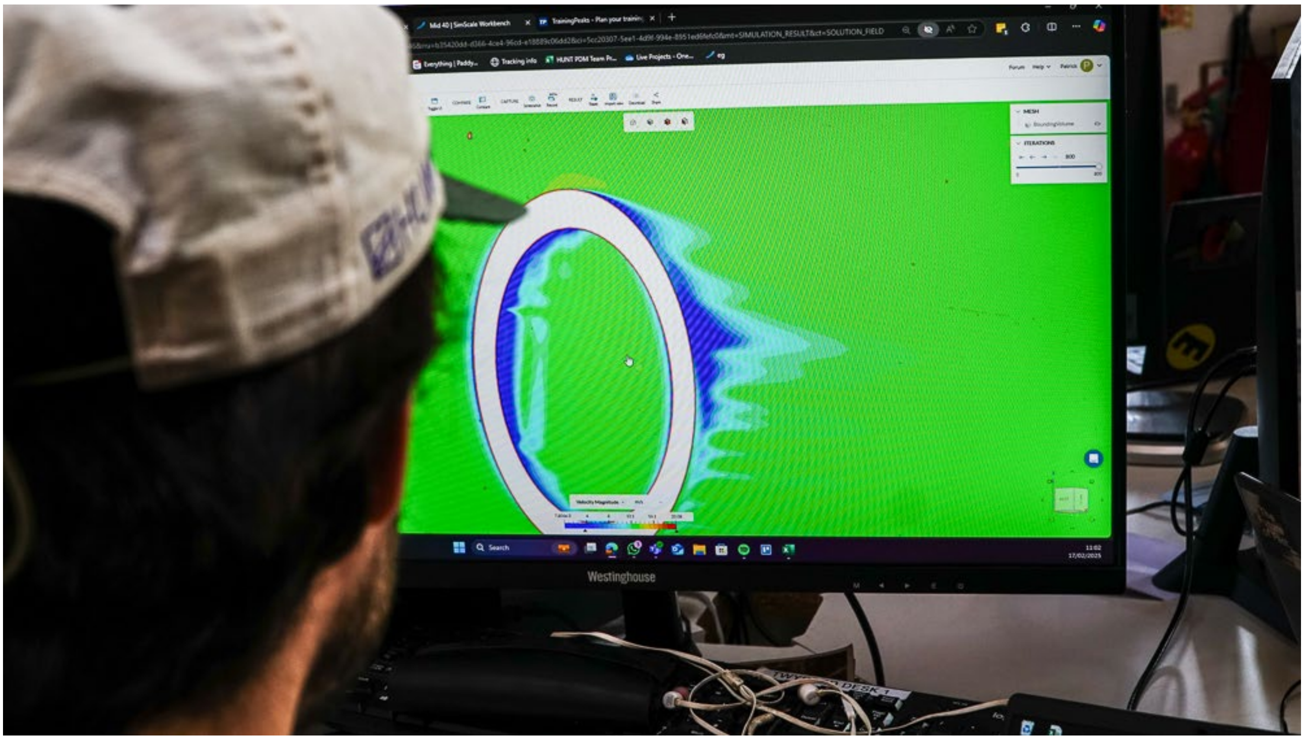
The main features of the rim design that can be altered are:

- Rim depth
- Outside width
- Nose radius
- Sidewall profile (e.g. curved/straight)
- Bead shape/thickness

With most of these features there will be a weight penalty due to adding material which needs to be balanced against the potential aerodynamic gains.

The initial tests on the front wheel are run as wheel-only simulations as this allows simulations to be run for a smaller quantity of computational resources whilst still gathering useful results. This is reasonable as modern bikes with wide fork blades lead to minimal interaction between the wheel and fork. Full bike simulations then follow before the final profiles are selected.




Westinghouse

The profiles are simulated from 0° up to 15-20° yaw angle as this is normally enough to understand where the airflow transitions from laminar to turbulent around the rim and therefore where the tyre and wheel profile stalls. Stalling is when the air flow separates from the surface of the rim causing high drag. This yaw angle range also covers the wind angles that riders will encounter most often. Wind angles over 15 degrees are unusual (and the WAD takes this into account) but this is a situation where the steering moment experienced by the rider is accentuated leading to a feeling of instability. Above 15 degree wind angles, although experienced less often, can have a significant effect on aerodynamic performance if stalling has occurred leading to airflow detachment.

The tyre used for this test was a 28mm Schwalbe Pro-One, which was scanned on the appropriate internal width rim using a hybrid laser and blue light scanner. Smoothing was then applied to the surface to minimise the computations required to create the mesh and resolve the flow around the tyre.

The rear profiles were initially simulated as wheel-only models to look at the performance of the wheel in freestream airflow. The process is quickly moved to testing in full bike simulations as the performance of the rear wheel is much more dependent on the interaction between the frame and the rear wheel.

This leads to different shaped profiles being effective as the leading edge of the rim is faired by the frame making the rim performance in this aspect less important. The performance on the trailing edge where the nose of the rim is meeting the air dictates the profile's performance most strongly.

Why are the Hunt Aerodynamicist Wheels deeper on the rear when Hunt Limitless wheels are the same depth front and rear? Hunt's patented Limitless Aero Width Technology used in the Hunt Limitless range of wheels allows deeper front wheel profiles without affecting stability. This is achieved through the unique Limitless construction method that allows a broader (34.5mm external) profile and larger nose radii without a significant weight penalty and allowing ETRTO compatibility with a 28mm tyre (ETRTO requires maximum 23mm internal rim width with 28mm tyres). For the Aerodynamicist range of wheels, it was decided to follow our competitors who cannot utilise the Hunt patented Limitless technology and thus Aerodynamicist wheels have a deeper rear as this could provide a balance of aerodynamics with parity in terms of stability to those leading competitors.

After a large number of different simulations have been run, the highest performing profiles will be 3-D printed as prototypes. In total, approximately 47, 000 hours of computing time were used for the six rim profiles. These prototypes are then used to validate the CFD-derived profiles in the wind tunnel.

Once production rim samples are available, these are then wind-tunnel tested against the current wheels and a range of competitor wheels.

Appendix 1 contains detailed technical information on the CFD processes used in this project as well as the methods used in the wind tunnel validation process. For a fully detailed example of the stages in this process please see a previous white paper report*:*

White Paper

3.0 Wind Tunnel Testing & Setup

The wind tunnel has been an extremely useful tool in measuring the performance of a wheelset in a controlled environment and therefore an integral part of the development process.

The GST Windkanal was used for this project. GST is a low-speed open wind tunnel constructed in 1986 for use by Airbus Space and Defence and is well suited for bicycle testing – used and recognised widely in the cycling industry for independent product development testing.

Final production test setup:
Bike: Specialized Tarmac SL8 (56cm)
Tyres: Schwalbe Pro One 28mm
Tyre Pressures: 50 psi (3.5 Bar)
Wind and Roller Speed: 45 kph
Yaw Angles: -20° to +20°.

The wind tunnel is an important tool in HUNT's aerodynamic development process. It permits changes to the tyre shape and size without having to analyse the model and adds in the realism of a full bike and makes swapping bikes very easy if. This is time consuming to do virtually. Also, the small details such a tread pattern are obviously present, but to get the best resolution of the small differences between similar wheels, testing is carried out with no rider, in laminar flow. This allows for fine but important marginal gains in drag to be picked up between runs.

3.1 Selection of competitor wheels

A range of competitor wheels was selected based on the below criteria:

- Wheelsets within the broad depth ranges.
- Wheelsets that have reasonable compatibility with ETRTO requirements (this would preclude wheelsets that would require excessively wide tyres in order to comply with ETRTO)

4.0 Aerodynamicist 54-58 Wheel Development

4.1 Purpose of the wheels

- Aero-first deep wheelset for fast, flat/rolling road riding and racing. Fastest on the market.

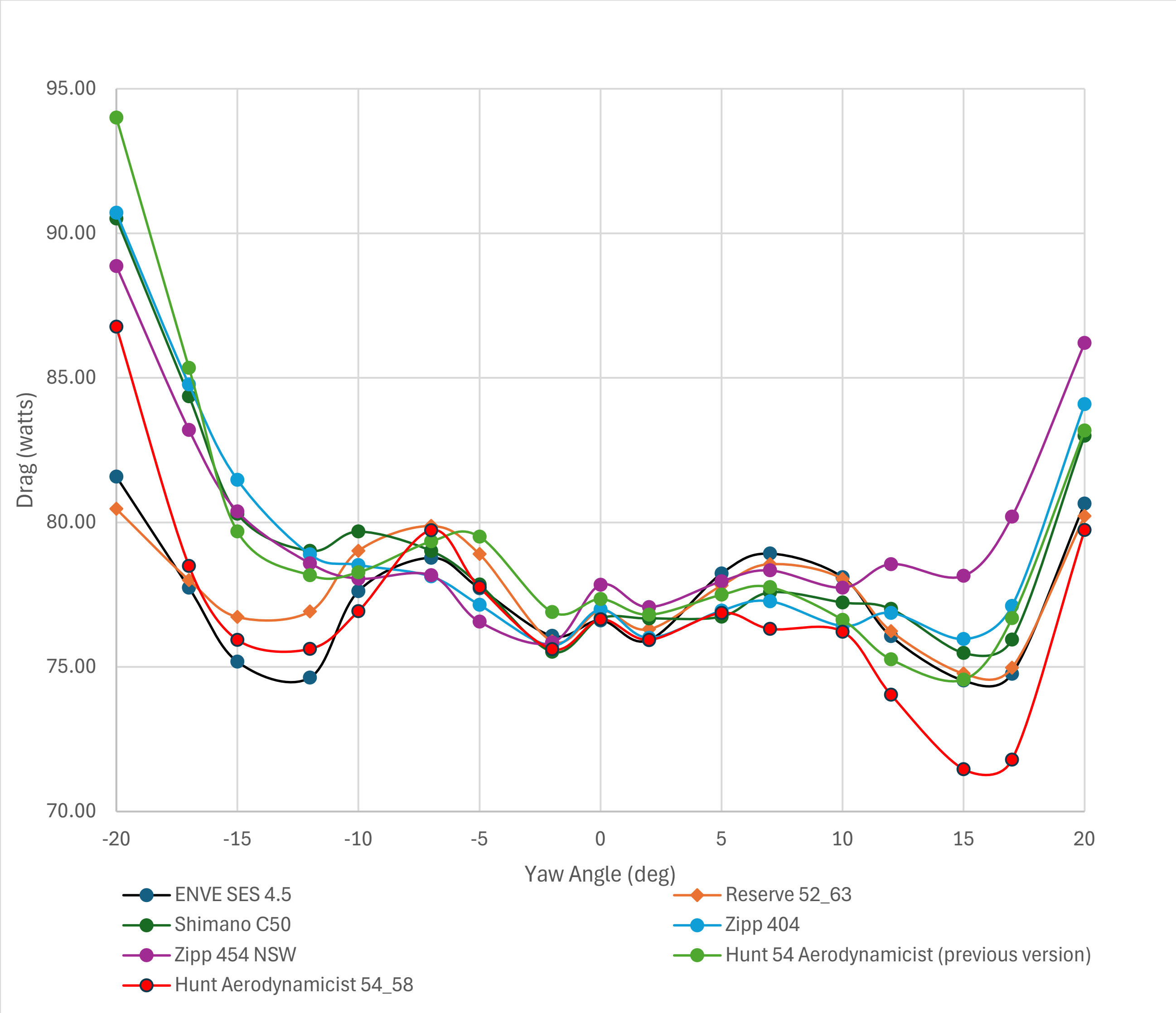
4.2 Results

Wheelset	Power Mavic WAD* (W)	% Change	Nominal tyre size (mm)	Measured width - ave (mm)	Averaged depth (mm)	Claimed weight w/o rim tape (g)	Actual weight w/rim tape(g)
Hunt Aerodynamicist 54_58 UD	74.84	0.0%	28	28.6	56	1391	1411
Enve SES 4.5	75.40	0.9%	28	29.6	53	1432	1473
Zipp 404 Firecrest	75.78	1.4%	28	28.9	58	1559	1573
Reserve 52/63	75.81	1.4%	28	29.8	57.5	1606	1631
Shimano C50	75.97	1.6%	28	28.1	50	1461	1474
Hunt 54 Aerodynamicist-previous generation	76.25	2.0%	28	28.0	54	1410	1429
Zipp 454 NSW	76.28	2.0%	28	28.5	55.5	1428	1464
Roval Rapide CL II**	77.96	4.3%	28	28.3	55	1590	1571
Hunt 4 Season Pro Disc (alloy)	88.10	17.9%	28	28.2	25	1535	1535

* Wind Average Drag (WAD) – see Appendix 1. **Round spoke non CLX version tested for closer pricing match.

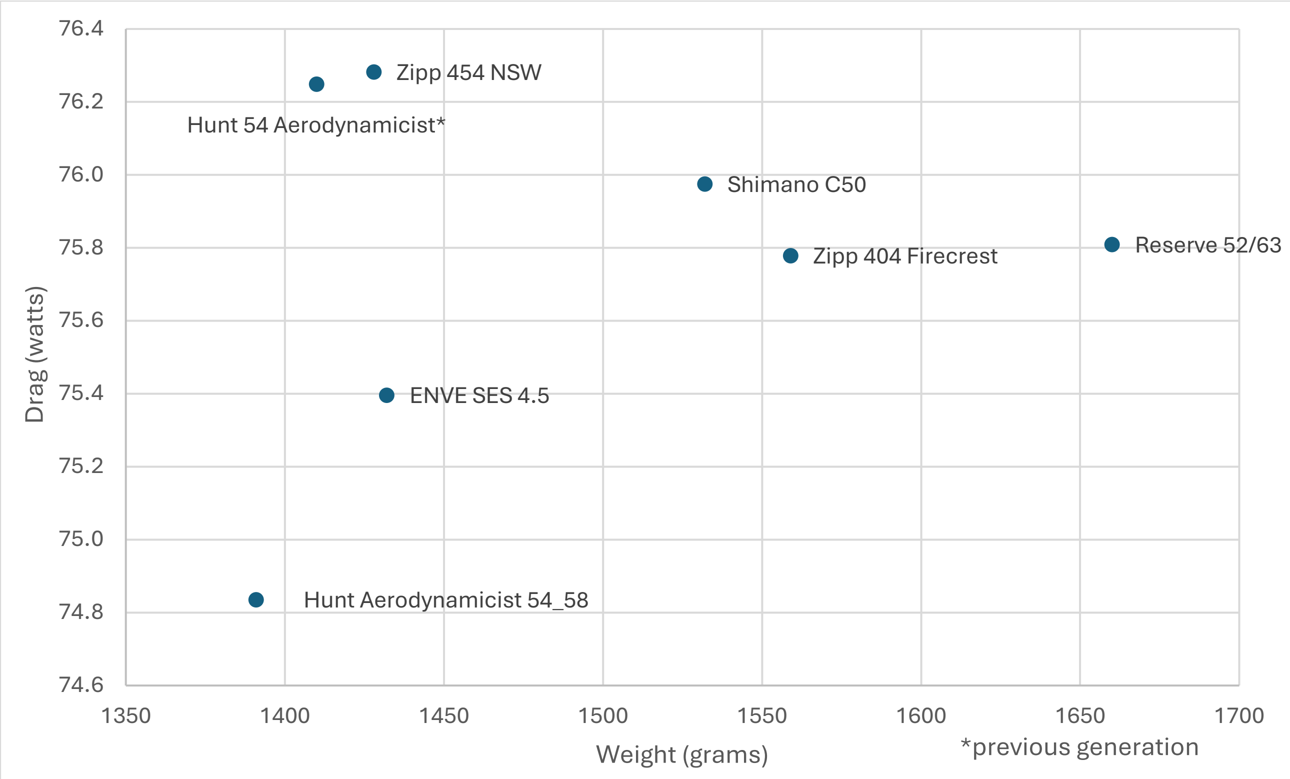
5.0 Performance analysis

5.1 Aerodynamic Performance



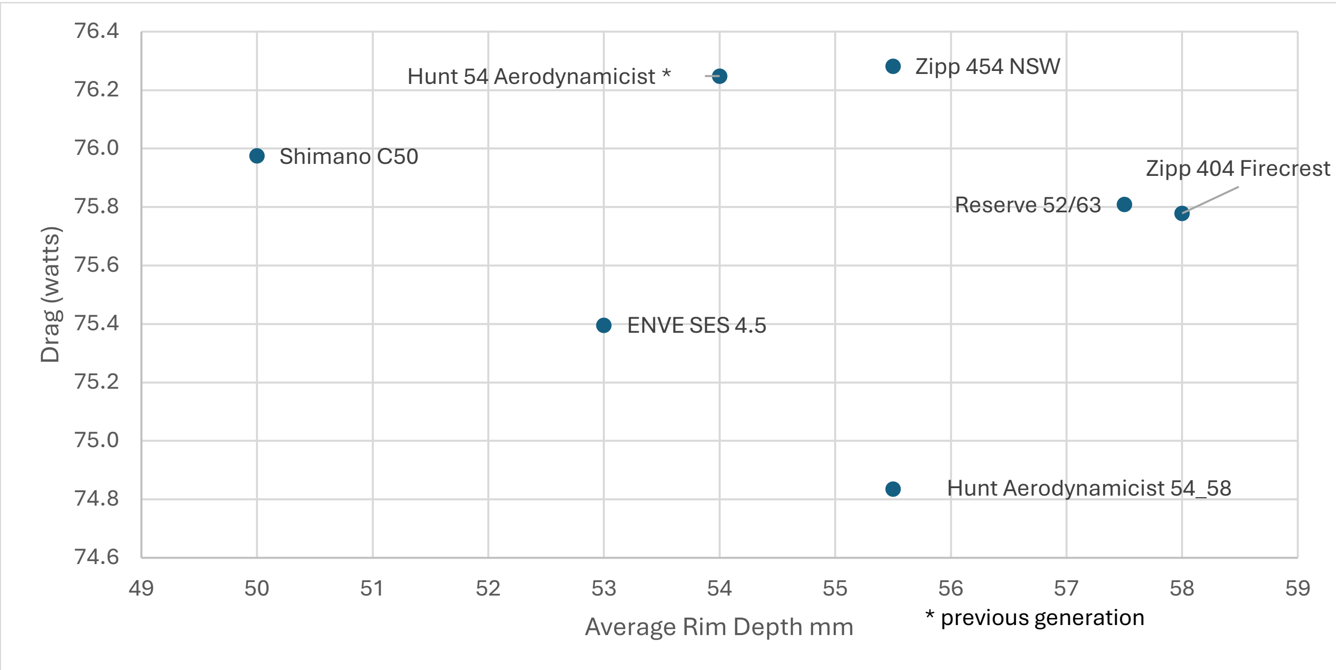
The Hunt Aerodynamicist 54_58 was the clear leader in terms of aerodynamic performance, being over 0.5 watts faster than the nearest competitor on the Mavic WAD scale, the Enve SES 4.5. The new Hunt Aerodynamicist 54_58 wheel showed a 2% reduction in system drag when compared to the previous version, the 54 Aerodynamicist. The front profile of the 54_58 performs through a wide range of yaw angles displaying lower drag at high yaw angles, due to the sailing effect achieved and the delayed stalling of the profile.

5.2 **Drag v Weight**

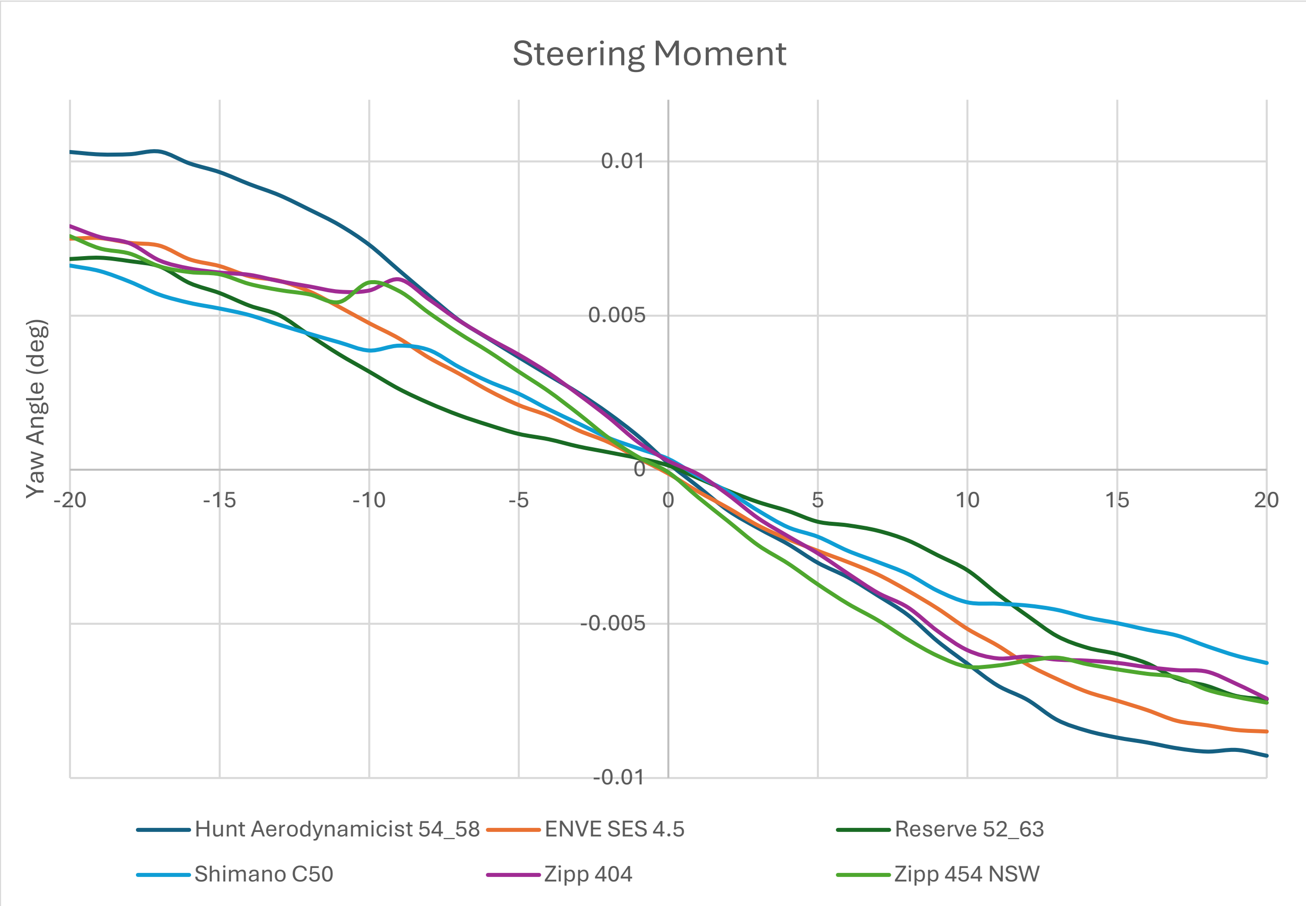


The Hunt Aerodynamicist 54_58 was the clear leader when considering the combination of weight and low drag.

5.3 **Drag v Depth**



5.4 Steering Moment



Perceived wheel stability can be demonstrated by looking at the steering moment, which is derived from the side force experienced by the wheel, modified to take account of wind speed and atmospheric pressure. In the above graph the new Hunt Aerodynamicist 54_58 wheels have a smooth curve throughout all the measured yaw angles. The steering moment is linear and predictable which will be felt as stable feedback through the handlebars. Some of the competitor wheels show evidence of obvious stalling where the curve shows a sudden inflection. This would be noticed as a sudden change in the steering forces felt by the rider.

6.0 Conclusions Aerodynamicist 54-58

The project has fulfilled the initial brief, which was to produce a very stable wheelset with improved aerodynamics without the obvious route of just increasing the depth, which usually adds weight. The new Aerodynamicist wheels showed a reduction in the Mavic WAD figure of 1.4 watts. Despite a depth increase of 4mm in the rear wheel, the wheelset weight was reduced from 1410 grams to 1391 grams. This 18-gram reduction was achieved through innovative layup design.

7.0 HUNT Aerodynamicist 44_46 Wheel Development

7.1 Purpose of the wheels

Aerodynamically optimised mid-depth wheelset designed for versatility and speed across varied terrain.

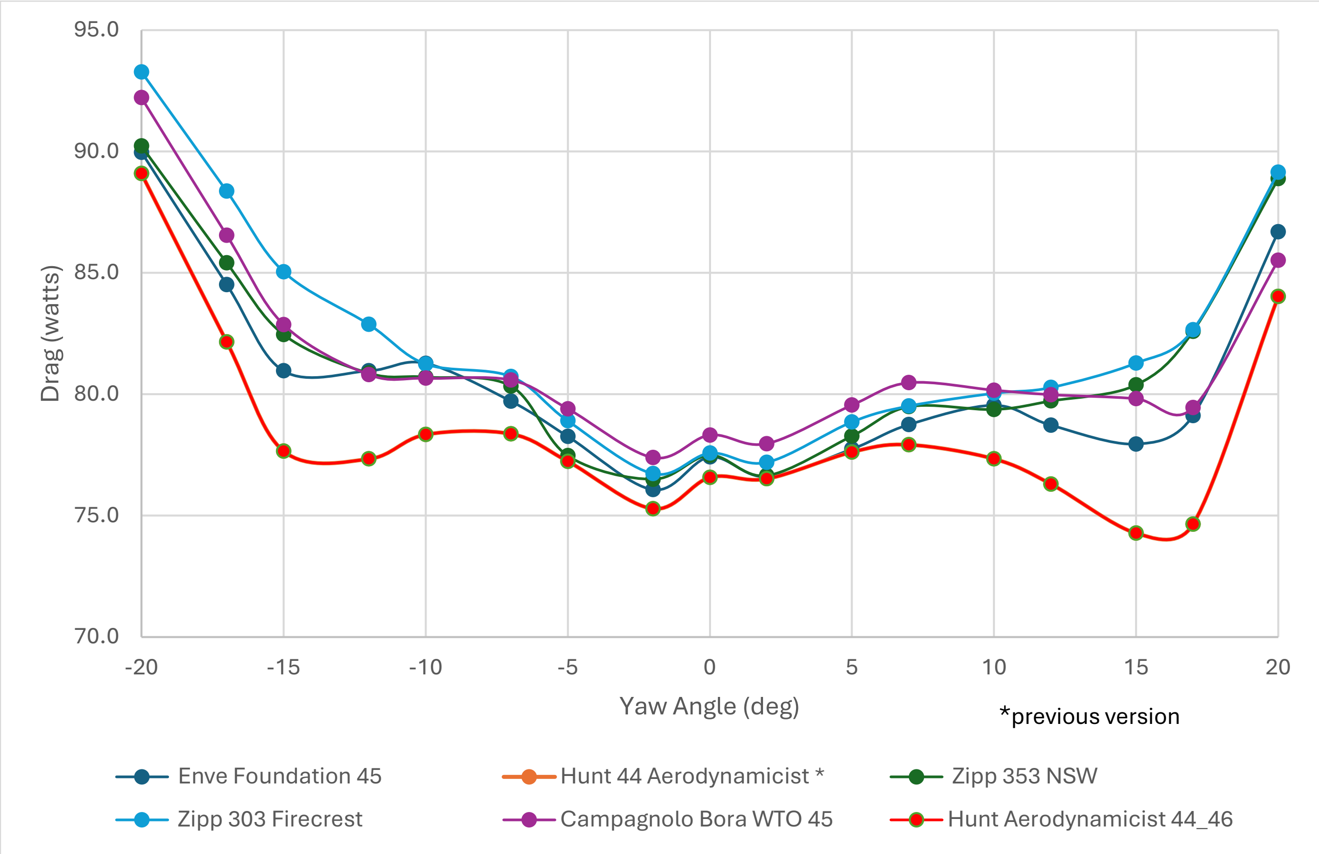
7.2 Results

Wheelset	Power Mavic WAD* (W)	% change	Nominal tyre size (mm)	Measured width - ave (mm)	Averaged depth (mm)	Claimed weight w/o rim tape (g)	Actual weight w/rim tape(g)
Hunt Aerodynamicist 44_46 UD	75.56	0.0%	28	28.3	45	1274	1294
Mavic Cosmic 45 SL	76.35	1.0%	28	27.2	45	1575	1465
Enve Foundation 45	76.97	1.9%	28	27.7	45	1513	1603
Hunt 44 Aerodynamicist-previous generation	77.29	2.3%	28	27.5	44	1352	1352
Zipp 353 NSW	77.33	2.3%	28	29.8	45	1308	1367
DT SWISS ERC 1400 45	77.41	2.5%	28	28.3	45	1528	1528
Zipp 303 Firecrest	78.03	3.3%	28	29.3	40	1408	1407
Campagnolo Bora WTO 45	78.03	3.3%	28	28.8	45	1496	1434
Zipp 303S	78.03	3.3%	28	28.5	45	1530	1560
Hunt 4 Season Pro Disc (alloy)	88.10	16.5%	28	28.2	25	1535	1535

* Wind Average Drag (WAD) – see Appendix 1.

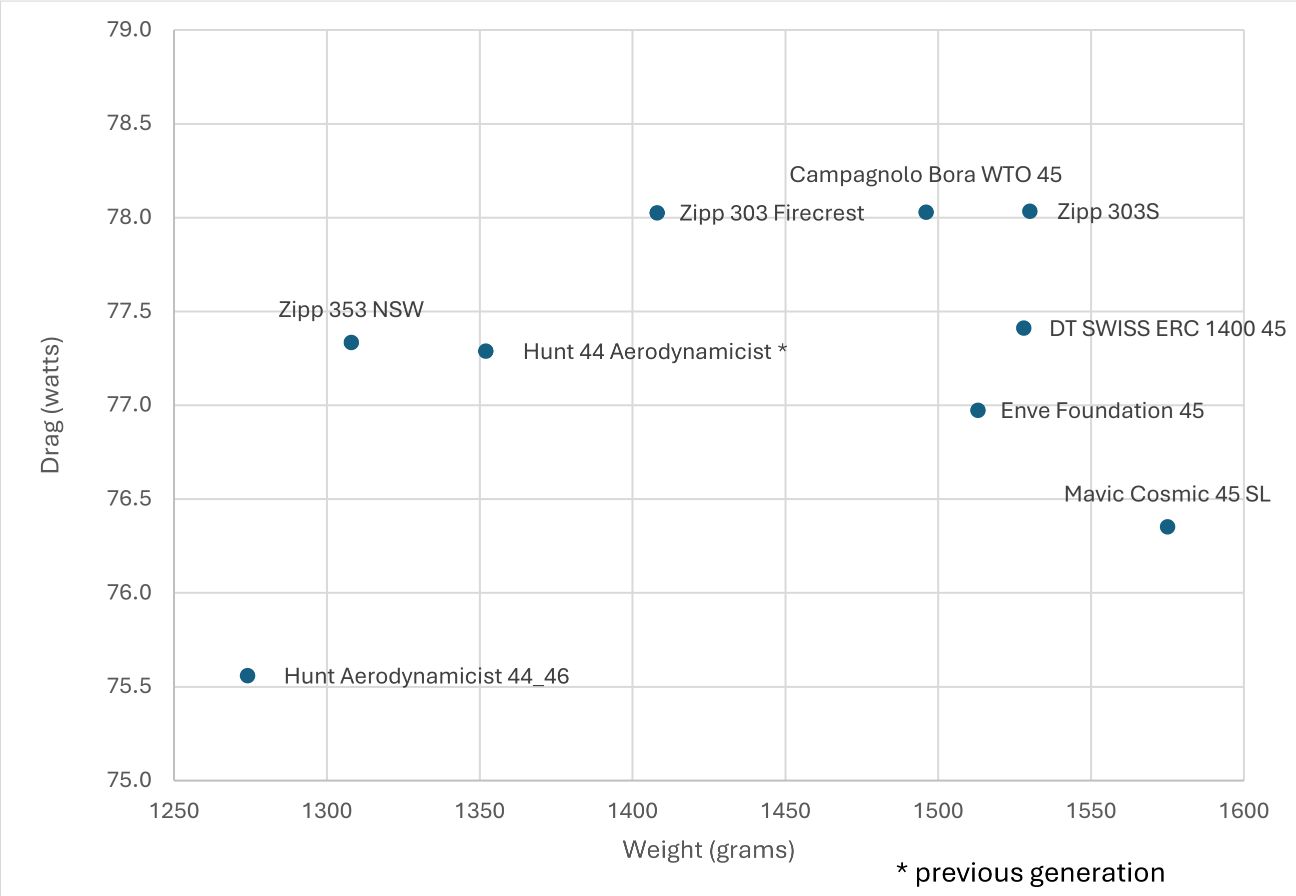
8.0 Performance analysis

8.1 Aerodynamic Performance

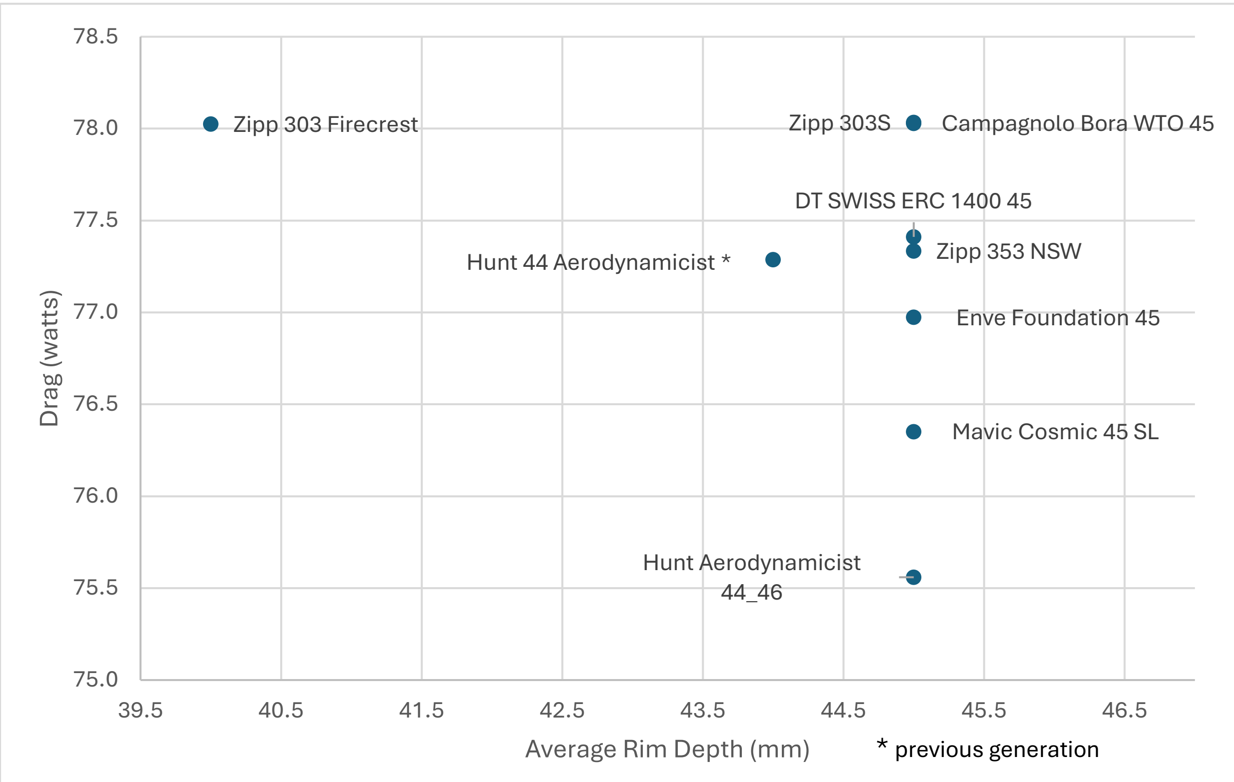


The Hunt Aerodynamicist 44_46 was the clear leader in terms of drag figures using the Mavic WAD comparison. Across almost all the yaw angles they were faster than all the competitor wheels tested, especially above 10 degrees yaw where the width (31mm) of the aerodynamicist front profile allows the wheel to sail more efficiently and stall later than the competitor set. At plus 5 degrees the Enve wheels were only 0.1 watts faster, well below the wind tunnel measurement error of 0.5 watts. The Hunt wheels performed particularly well at higher yaw angles (over 7.5 degrees) but were still ahead of most of the competitor wheels at lower yaw angles.

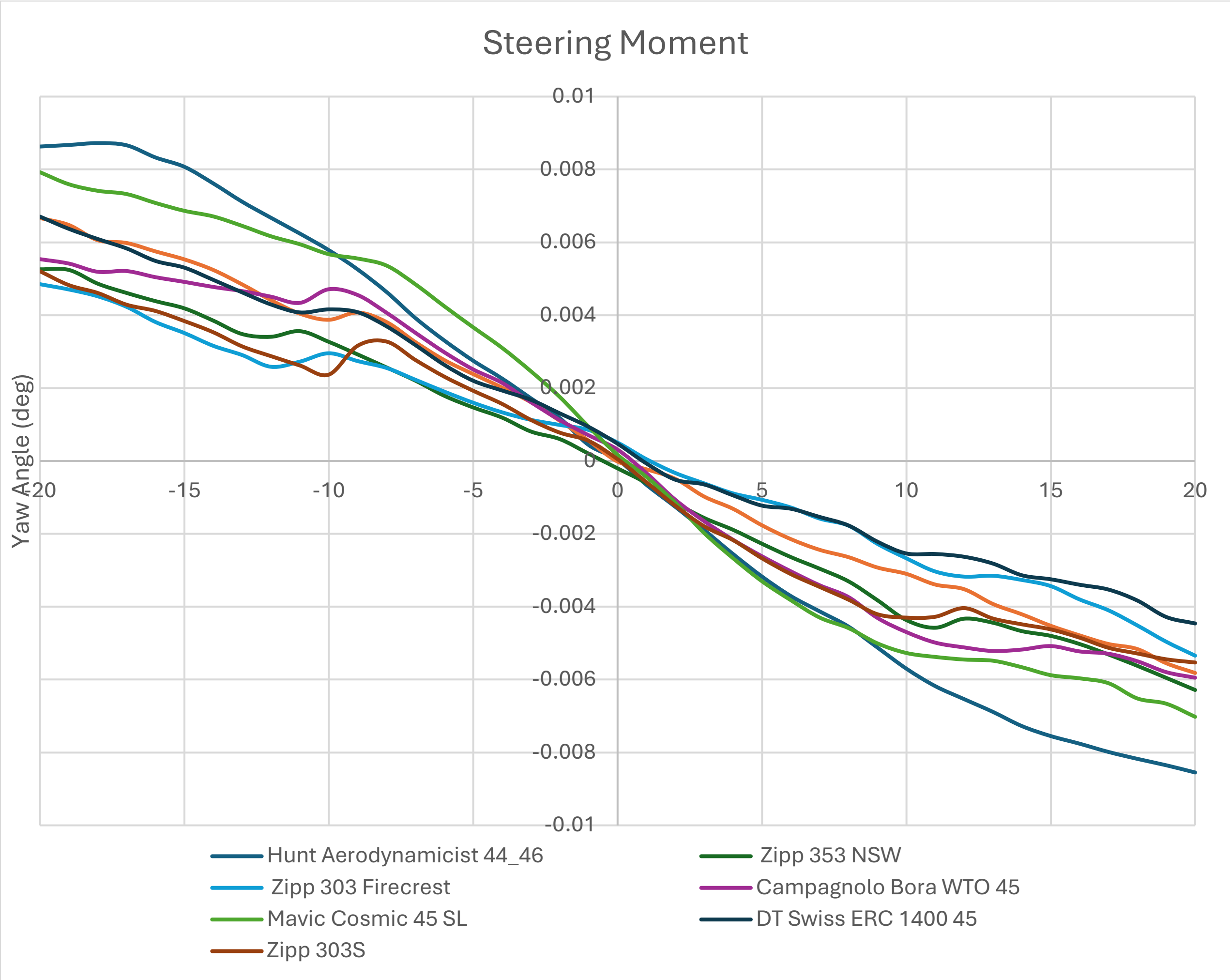
8.2 Drag v Weight



8.3 Drag v Depth



8.4 Steering Moment



Perceived wheel stability can be demonstrated by looking at the steering moment, which is derived from the side force experienced by the wheel modified to take account of wind speed and atmospheric pressure. In the above graph it can be seen that the new Hunt Aerodynamicist 44-46 wheels have a smooth curve throughout all the measured yaw angles. The steering moment is linear and predictable which will be felt as stable feedback through the handlebars. Some of the competitor wheels show evidence of obvious stalling where the curve shows a sudden inflection. This would be noticed as a sudden change in the steering forces felt by the rider.

9.0 <u>Conclusions Aerodynamicist 44_46</u>

The project has fulfilled the initial brief, which was to produce a very stable wheelset with improved aerodynamics without the obvious route of just increasing the depth, which usually adds weight. Despite a depth increase of 2mm in the rear wheel, the wheelset weight was reduced from 1352 grams to 1274 grams. The 78-gram reduction was achieved through innovative layup design.

10.0 Aerodynamicist 34_34 Wheel Development

10.1 Purpose of the wheels

Superlight climbing wheel with optimized aerodynamic shaping for hilly/mountain terrain.

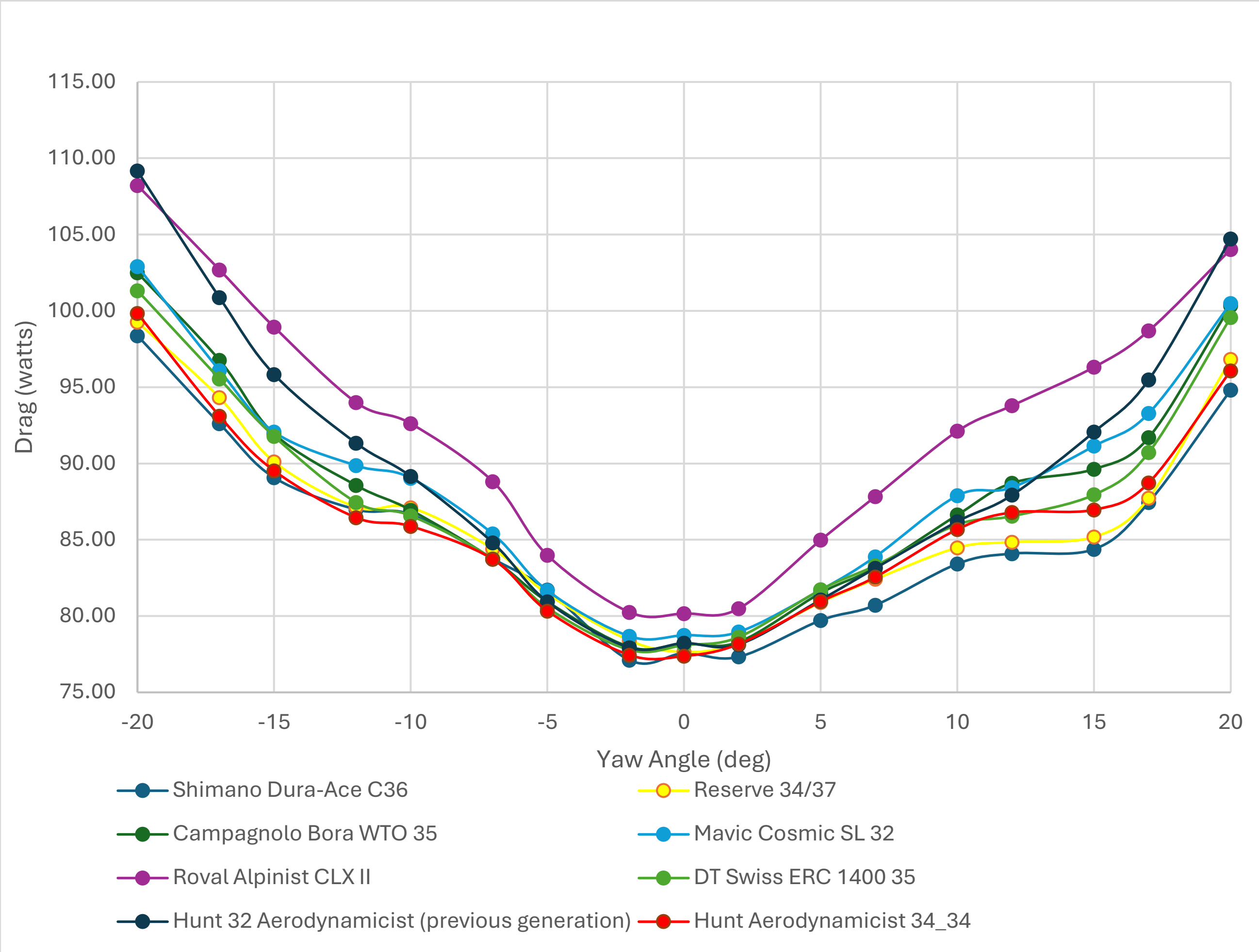
10.2 Results

Wheelset	Power Mavic WAD* (W)	% Change	Nominal tyre size (mm)	Measured width ave (mm)	Ave depth (mm)	Claimed weight w/o rim tape (g)	Actual weight w/rim tape(g)
Shimano Dura-Ace C36	80.16	-0.7%	28	28.8	36	1478	1368
Hunt Aerodynamicist 34_34 UD	80.74	0.0%	28	29.4	34	1175	1196
Reserve 34/37	80.92	0.2%	28	29.3	35.5	1392	1343
DT Swiss ERC 1400 35	81.37	0.8%	28	28.4	35	1477	1477
Campagnolo Bora Ultra WTC 35	81.70	1.2%	28	29.1	35	1285	1332
Hunt 32 Aerodynamicist (previous generation)	82.39	2.1%	28	27.7	32	1213	1213
Mavic Cosmic 32	82.49	2.2%	28	28.7	32	1499	1481
Hunt 34 Aero Wide Disc (alloy)	82.66	2.4%	28	28.3	34	1565	1565
Roval Alpinist CLXII	85.65	6.1%	28	28.7	33	1265	1358
Hunt 4 Season Disc (alloy)	88.10	9.1%	28	27.0	25	1535	1535

* Wind Average Drag– see Appendix 1.

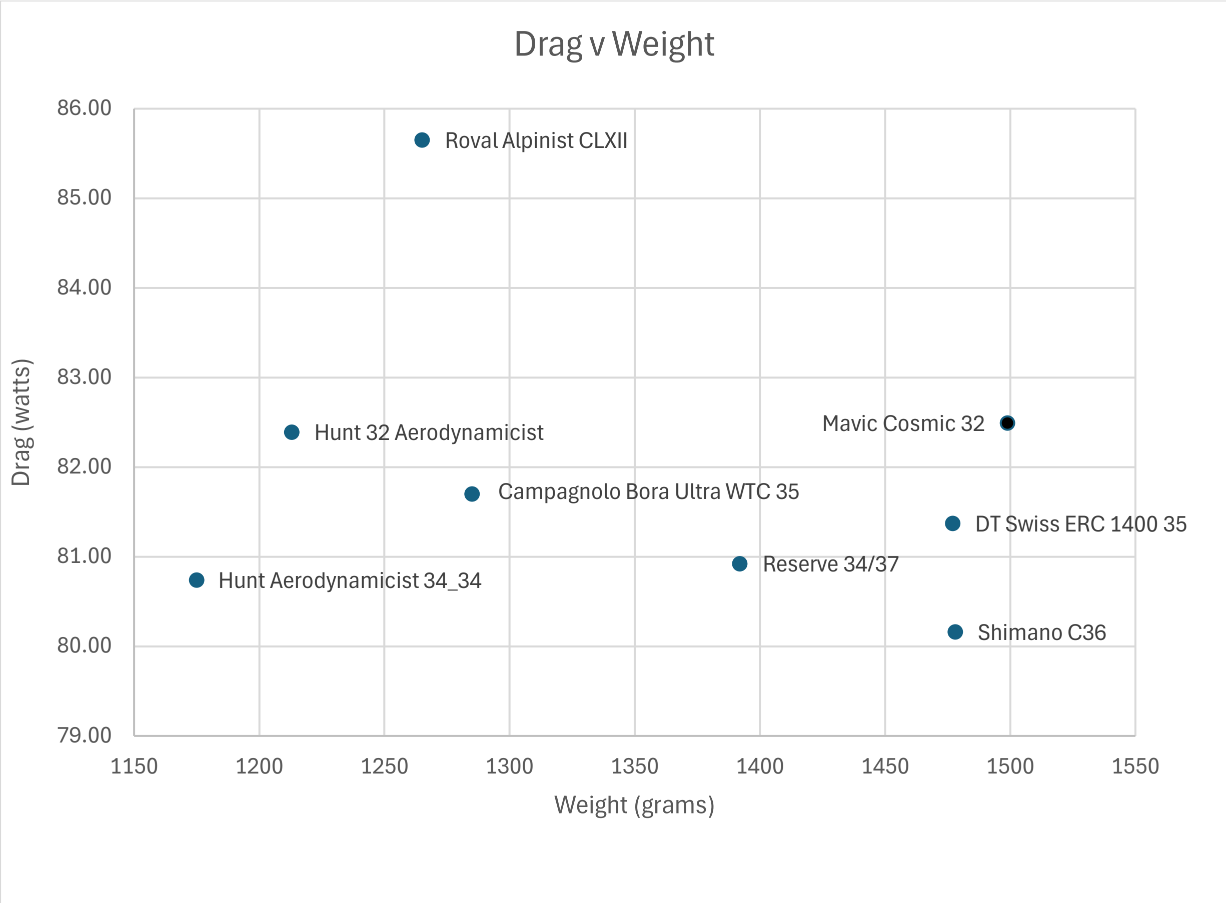
11.0 Performance analysis

11.1 Aerodynamic Performance



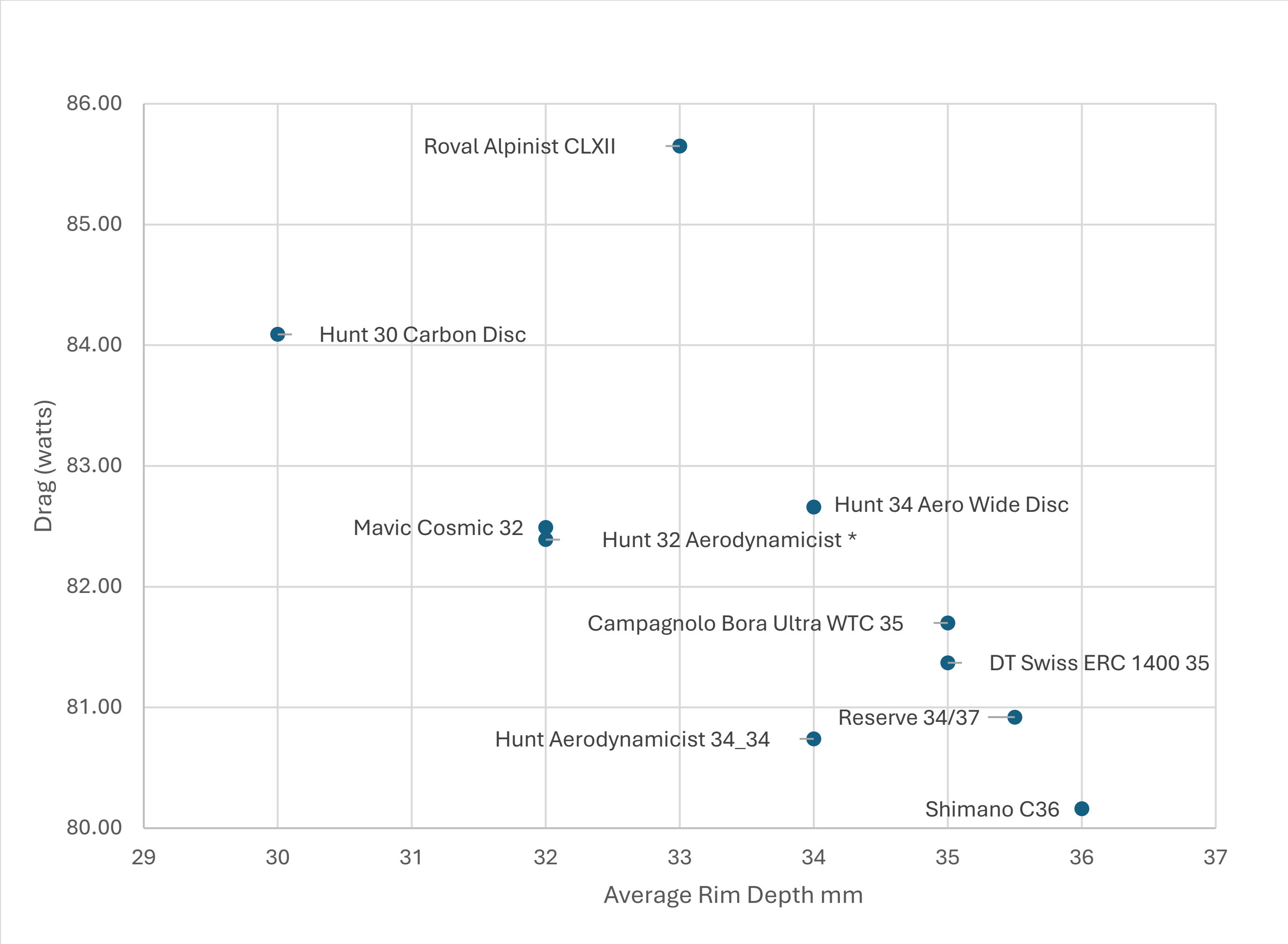
The new Aerodynamicist 34_34 wheelset outperformed all the other wheels in terms of drag, except for the Shimano Dura-Ace C36. Our previous WT tests of deeper Shimano wheels meant we did not expect the C36 to perform well and so we did not CFD model it. The result was that we didn't win here but the C36 is 172g heavier. We respect Shimano for making an impressively aerodynamic wheel in the C36. The purpose of the wheels (section 10.0) required the weight to be kept to a minimum so as to ensure that this wheelset was suitable as a climbing wheel. This was achieved by keeping the rim depth slighter shallower whilst optimising the aerodynamic performance. The next nearest competitor in terms of drag is the Reserve 34/37 wheelset which comes in at over 200 grams heavier.

11.2 Drag v Weight



The aim with this wheelset was to produce a shallow section wheel with excellent aerodynamic performance, but at a weight that would enable it to be used as a mountain climbing wheel. The only competitor wheel that was faster than the new Aerodynamicist 34_34 was the Shimano Dura-Ace C36, which carried a weight penalty of over 178grams per wheelset, this for a drag reduction of only 0.58 watts.

11.3 Drag v Depth



The Shimano Dura-Ace C36 achieved the drag reduction through increased rim depth with an increase in weight.

12.0 Conclusions Aerodynamicist 34_34

The project has fulfilled the initial brief, which was to produce a wheelset with improved aerodynamics without adding weight. The new Aerodynamicist was 1.65 watts faster than the older version using the Mavic WAD measurement. Despite an increase in rim depth of 2mm, the wheelset weight was reduced from 1214 grams to 1175 grams. This 39-gram reduction was achieved through innovative layup design.

13.0 New Aerodynamicist Range Comparison

Hunt Wheelset	Power Mavic WAD* (W)	% Change
Hunt Aerodynamicist 54_58 UD	74.84	0.0%
Hunt Aerodynamicist 44_46 UD	75.56	1.0%
Hunt Aerodynamicist 34_34 UD *	79.34	7.8%
Hunt 4 Season Disc (alloy)	88.10	16.4%

*Mavic WAD drag figure adjusted for wind tunnel runs on different days/conditions.

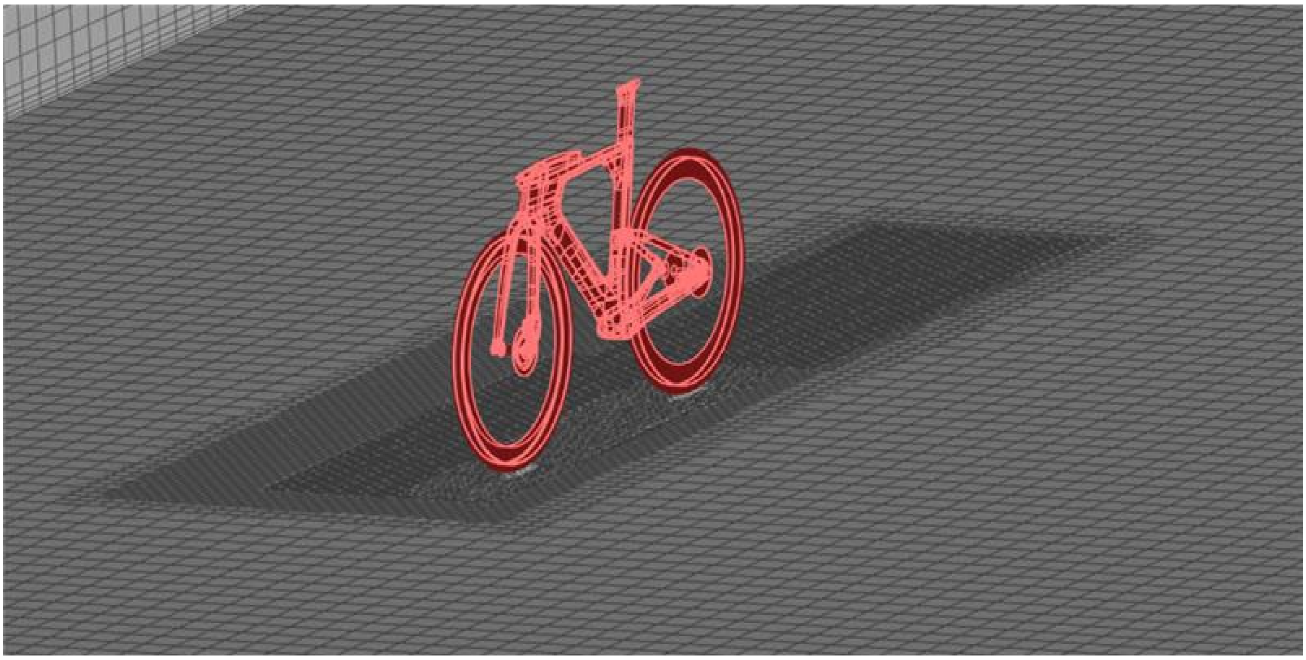
Appendix 1: HUNT Rim Design Methodology

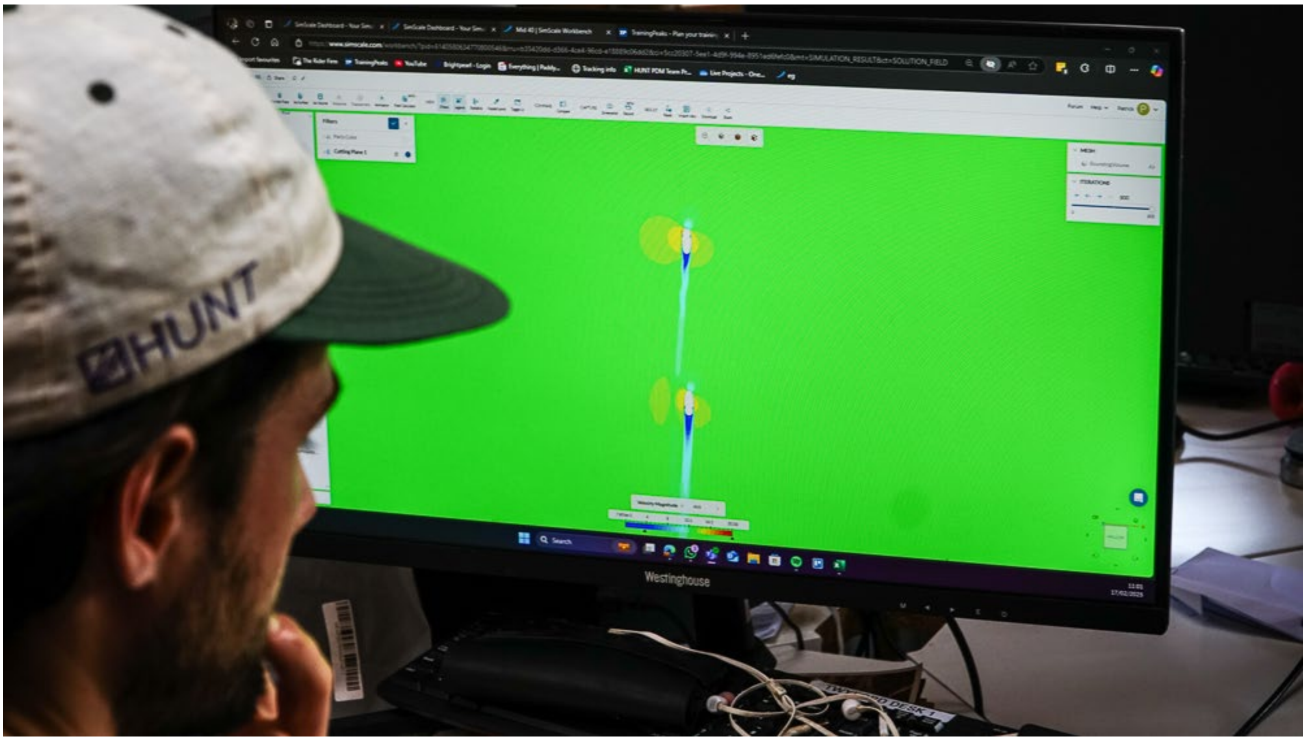
There are three primary tools currently used for measuring aerodynamic drag when developing bicycle components:

1. Wind tunnel testing – widely accepted as the industry standard for testing completed products. It generates reproducible and reliable results and allows testing over a range of wind yaw angles.
2. GPS based track testing – uses a GPS locator combined with power data to measure aerodynamic drag. It cannot be used to measure drag at non-zero yaw angles and relies on consistent rider position to measure component performance. In addition, current techniques result in error values of +/- 3 watts which is in excess of the typical power loss differences between the current best performing wheelsets on the market.
3. CFD – uses a finite element analysis to compute the airflow through a 'mesh' constructed around a computer-generated model of the shape.

CFD allows the iteration of a number of rim shapes by simulating airflow over the rim/wheel. These iterations are entirely created by the software and allow the designer to optimise the shape before committing to a 3D printed sample. It also allows the inclusion of a complete bike with front and rear wheels to indicate how the rim will perform in the disturbed airflow created as the air flows through and around the bike.

However, the inclusion of all the finer details of wheel and bike design (e.g. spokes/nipples/tyre tread and surface texture etc) will hugely increase simulation time and can often make the model impossible to solve. Using the wind tunnel yields results that reflect all of those fine details, but CFD allows much more refinement to the prototype designs before they are printed and tested in the wind tunnel.





Additionally, the wind tunnel test is then approached with predictions of the performance outcome. This not only speeds up the process but helps validate the accuracy of the model. It also allows rapid changes of different tyres and rims.

It was previously decided to test wheels using the wind tunnel at GST in Immenstaad, Germany. GST is an open wind tunnel, constructed in 1986 for use by Airbus Space and Defence. It is now independently operated, and as a low-speed tunnel it is well suited for bicycle testing. The tunnel has been used widely across the cycling industry including by Tour Magazine for their independent aerodynamic testing.

Another key benefit of CFD is the capability to visualise fluid flow through pressure, velocity and streamline plots to analyse results and contributing to profile modifications.

The front and rear wheels operate in different environments. The front wheel passes through largely undisturbed air and also influences the airflow over the frame and rear wheel. The rear wheel is shielded by the bike in front, the airflow is more turbulent, and more head on (as the frame and front wheel will have redirected the airflow to some extent). This means that most of the aerodynamic benefit comes from the front wheel, but also that rim designs can be optimized differently for front and rear wheels.

Many aerodynamic wheels are designed with a deeper rear wheel and a shallower front wheel. This is primarily driven by concerns over the handling of deeper section front wheels. However, since the front wheel has the largest impact on aerodynamic performance, that additional depth (and corresponding weight) is being used at the rear wheel where the drag benefit is lower. Hunt Limitless Technology use in several Hunt Limitless Aero wheels negates this issue through adding front wheel width and thus stability with low drag and minimized weight.

Wind averaged drag (WAD)

When assessing the aerodynamic performance of a wheelset, it is necessary to consider the performance of the wheel in a variety of different 'yaw angles' – i.e. the effective angle of wind the rider is experiencing as they ride. Because the rider is moving forwards this will be affected by the rider's speed, the wind angle and the wind speed.

The time spent at any given yaw angle will be different, depending on the conditions and route. To give a consistent method for combining these yaw angles into a single WAD value Mavic has developed and published a 'ponderation law'. Wind angles over 15 degrees are unusual (and the WAD takes this into account) but this is a situation where the steering moment experienced by the rider is accentuated leading to a feeling of instability. Above 15 degree yaw angles, although experienced less often, can have a significant effect on aerodynamic performance if stalling has occurred leading to airflow detachment.

The GST wind tunnel can take measurements between -20^o and + 20^o, so the values above and below 20^o have been removed from the weighting.

CFD process

The initial development of the rim shapes is conducted using computation fluid dynamics (CFD) techniques carried out by HUNT's in-house engineering team on a number of different profiles. This CFD model and the resulting design proposals are later validated with wind tunnel testing. This wind tunnel testing includes 3D-printed wheel models tested against major competitors. A final wind tunnel test with production samples versus the full competitor set is then used to validate the performance of the production wheels.

This combined approach with CFD and wind tunnel testing has been used by the HUNT team several times, including for the development of HUNT's 73/87 Triathlon wheels, the 60 Limitless and SUB50 wheelset.

In broad terms CFD uses a computer model to calculate the drag over an object in particular wind conditions. This is achieved by creating a 'mesh': a network of small cells that fill the space to be modelled, and generally become smaller closer to the surface of the model and in areas where the model's geometry is more complex.

The flow of the fluid (in this case air) is then solved across each of these cells. And then the results of these many solutions are collated to build up a picture of the flows around the geometry. From this the pressure and drag being enacted on the geometry by the fluid flow can then be calculated by the model.

- Two computational models are used during the iteration stage: a simplified wheel only model of a rim and tyre, then for further detail of the leading profiles a bike and wheel model. The bike and wheel model is particularly important for assessment of rear wheel designs.

- When using CFD no physical model needs to be produced, assembled, transported, and tested vastly reducing the cycle time for testing, comparing and improving designs, from months to days. Although a very valuable tool any CFD model is a simplification of the real-world system with some of the complexity removed.

In these models there are two particularly important simplifications:

- The model does not include the hub or spokes. Modelling these in rotation requires vastly more computational power and introduces more uncertainty. Experience shows that modelling the rim and tyre is sufficient to differentiate rim designs and results are reflected well in wind tunnel testing.

- The model introduces a smoothed radius of 0.2mm where the tyre meets the rim sidewall. Attempting to create a finer radius than this makes it very difficult to resolve the mesh with an acceptable number of elements and associated computing power. x

These factors and simplifications are controlled across all rim designs so each profile is evaluated in the same conditions.

The best performing designs are all subsequently tested in the wind tunnel where all the details of the tyre, wheel components and the complete bike will input into the final selection of the best design and comparison to competitors.

CFD Methodology – Wheel only

For the wheel only model the design to be tested is placed one third of the way into the computational wind tunnel domain and with a small gap between the tyre and the ground.

After finalising the optimal mesh for the geometry above, the next step is to apply the initial and boundary conditions which define the constraints of the external aerodynamic analysis of a bicycle wheel which are applied to the virtual domain to replicate the setup and conditions.

The wheel is simulated over a range of yaw angles and the raw drag and side force values are extracted from the profile. Since this a symmetrical model of the rim and tyre, only positive yaw angles are used. Simulations are run to 16° to capture the stall point dynamics. Yaw angles above this represent flow separation and difficult to model in CFD; they are best assessed with measurements in the wind tunnel.

CFD Methodology – Complete Bike

After shortlisting the best performing designs these are analysed with the complete bike.

The bike modelling is particularly important when developing the rear profiles due to the interaction of flow with all of the upwind components, so for the development of the rear wheel this is the primary development tool.

It has been decided to focus on positive yaw angles on the non-drive side to make the most efficient use of computing resources, along with the simplifications described above. Generally, the asymmetry of the drag curves observed in the wind tunnel are because of the drivetrain affecting the airflow, and experience has shown that single-sided modelling is sufficient to generate a range of well performing designs for further testing in a wind tunnel with a complete bike.

Outcome of CFD

As with any test, it is important to understand there is error associated with wind tunnel-based measurement and simulation approximations from CFD. The wind tunnel error has been found to be 0.3 watts, the effect of this is minimised by always using the identical tyres at the same pressure. Key comparative testing is done back-to-back to reduce the effect of any environmental or tyre shape changes throughout the day.