The HUNT LIMITLESS 48 AERO DISC: Designing and testing the world's most aerodynamic disc brake wheelset up to 50mm depth.

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Abstract

The adoption of disc brakes in professional and amateur road cycling has created an opportunity for new wheelset designs, where the rim shape is no longer restricted by the need to act as the braking surface for caliper brakes.

The authors set out to create a highly aerodynamic road race specific wheelset, optimised around the wider 25mm and 28mm tyres that have become increasingly popular in road racing in recent years.

In the course of development, the team created the patent pending 'LIMITLESS' technology allowing the development of rim shapes that are wider than the tyre without adding excessive mass or compromising on tyre security.

The completed 48mm deep and 34.3mm wide rim profile used on the 48 LIMITLESS AERO DISC wheelset was tested against a range of the world's leading wheelsets at 50mm depth or below, using the wind averaged power analysis proposed by Mavic and was the most aerodynamic of the wheels tested with both 25mm and 28mm tyres.

1. Introduction

Bicycle wheel aerodynamics have been an active area of research and development since the late 1970s and the field has seen huge improvements in not only the aerodynamic performance but also the durability and usability of aerodynamic wheels.

In the 2010's most major wheel manufacturers settled on designs based around a few commonly accepted design features for optimum aerodynamics:

- Using the maximum depth permitted by the conditions of us – since larger rims depths typically have higher mass, are more sensitive to crosswinds and have at times been banned in some competitions.
- A maximum rim width that is close to or greater than the width of the tyre.
- A large radius of curvature at the spoke bed.

Many wheel and bike companies provide only limited wind tunnel and aerodynamic data, typically with a small number of data points and often comparing only to the company's own previous models. This makes it difficult for riders to compare the performance of products and make informed choices about what they ride. In this paper the authors aim to be as open as possible in providing meaningful data and comparisons to similar wheels currently available to riders from other companies. the authors have also included details of the development process and prototype testing results so that riders may see each step leading to the finished wheels.

1.1 The adoption of disc brakes in road cycling

In 2016 cycling's governing body the UCI began trialling the use of disc brakes in road cycling. This technology became fully authorised in 2018.

While initially perceived as having poorer aerodynamic performance attributed to presence of disc rotors; disc brakes have now become the default option for newly released aerodynamic road bikes, with the latest aerodynamic bikes from Specialized and Cannondale being released only in disc brake format.

These bikes have benefited from the greater flexibility of design that comes with use of disc brakes that no longer require the fork and seat stays to sit close to the wheel in order to mount a brake caliper. Additionally, brake calipers for disc brakes are placed behind frame structures for improved aerodynamic performance without the compromises on braking performance and ease of use that have been typical of hidden rim brake designs.

Similar and even greater advantages exist in designing aerodynamic disc brake wheels themselves. In rim brake systems the need to use the rim surface for braking in a rim brake wheelset imposes several design limitations:

- The maximum width of the rim in the area immediately below the tyre is limited to approximately 28mm to ensure the rim can fit between the brake calipers.
- The braking surface must be flat, and parallel or close to parallel to achieve good contact from the brake pads.
- The braking surface needs to be engineered to cope with the significant heat build-up from braking on long descents, as well as having sufficient thickness to cope with surface abrasion from braking.

By designing a wheelset and rim shape that is fully optimised for disc brake use, the authors were able to ignore these previous limitations on rim design with the intention to greatly improve on the performance of currently available disc brake wheelsets.

1.2 The increasing use of wider tyres and tubeless technology in road racing

A number of companies, media, and individuals have been carrying out testing on the benefits of using larger tyres with lower tyre pressures and the benefits that this gives to riders [1][2]. The benefits gained in grip and handling are widely accepted, but recent testing has also shown that wider tyres with lower pressures can also reduce rolling resistance. In addition, in certain cases the market leading performance tubeless tyres offer lower rolling resistance than tubular tyres that have traditionally been favoured by professional road racers [3].

Increasing numbers of professional riders have begun using larger tyres sizes, with 25mm now the norm and many riders choosing to use 28mm tyres, particularly in races with cobbled road sections. Current wheel designs have typically been optimised around the use of a 23mm tyre. When these wheels used with wider 25mm or 28mm tyres the excess difference between the tyre width and the external rim width often results in poorer aerodynamic performance when used with wider tyres. If rims are correctly optimised for wider tyres the aerodynamic differences between wider and narrower tyres will be reduced, and may be eliminated altogether, especially at higher yaw angles where the aerodynamic performance is more dependent on overall rim shape than frontal area.

Tubeless tyres are also becoming more popular in the professional peloton because of rolling resistance benefits and the fact that a tubeless set up can prevent punctures that might otherwise cost a rider a race victory [4].

Considering the benefits of wider tyres and tubeless technology the new HUNT wheelset would be designed to be optimised for use with 28mm tyres as well as ensuring excellent performance with 25mm tyres and would also be fully compatible with all tubeless tyres as well as non-tubeless clincher tyres.

2. The purpose of the wheels

The team established a design brief for the project:

- A wheelset specifically designed for mass-start road race use
- Optimised for the best aerodynamic performance with wider 25mm and 28mm tyres
- A rim designed specifically for disc brake bikes
- A hooked rim design to ensure compatibility with tubeless and non-tubeless clincher tyres
- A tyre bed design compliant with the latest ETRTO tubeless standards

Key dimensions for the wheelset were determined:

- The rim depth was set at 48mm providing exceptional aerodynamic performance whilst maintaining the handling, stability and low mass required for professional, elite and amateur road racing.
- The internal rim width was set at 22.5mm – providing a stable tyre profile with a wide base whilst still ensuring a safe and secure tyre fit.

Importantly the external rim width was not specified at this point – the design was left open to develop whatever shape would be most beneficial.

3. Design principles and initial proposed designs

The team identified some key possible design features, which when used together had the potential to create improved aerodynamic performance against the current leading rim designs:

- Using the shape of the rim in combination with a tyre to create an approximation of a National Advisory Committee for Aeronatics (NACA) published aerofoil shape, but with a truncated trailing edge. This truncated shape ensures that the rim design will perform well at a wide range of wind yaw angles.
- The NACA profile used was set at 100mm deep with the trailing edge truncated. A transition to a large radius of curvature around the rim bed allows for a smoother transition of the airflow especially at higher wind yaw angles.
- The use of this NACA profile places the widest point of the whole cross section slightly below the base of the tyre, with this point wider than the tyre width by approximately 4mm.

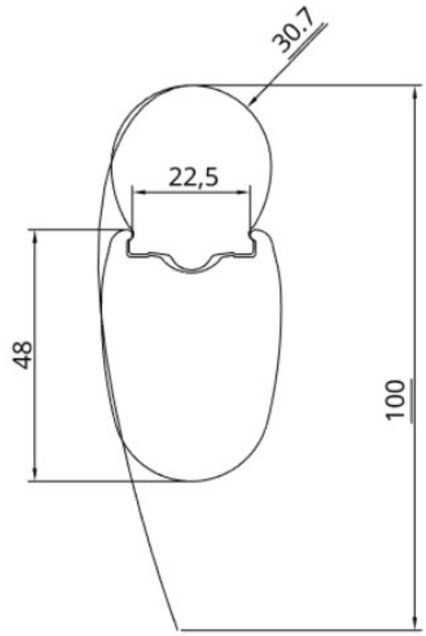

Figure 1 Illustration of the truncated NACA profile approximation used in designing the initial rim profiles

Within these principles, proposed rim shapes were developed combining elements of different widths, radii of curvature on the sidewall and rim bed, and different shapes around the rim tyre interface. The first five prototypes are shown below:

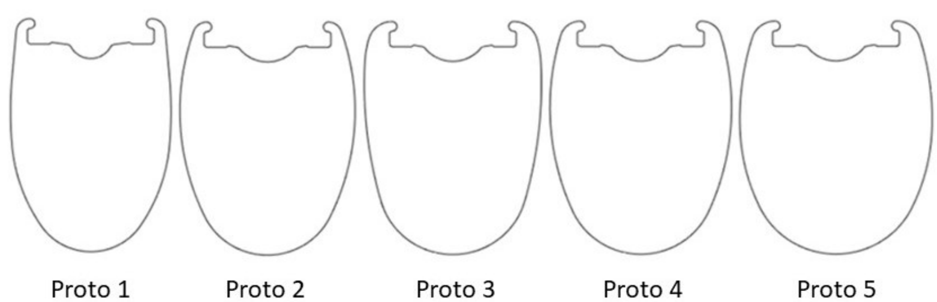

Figure 2 Cross sections of the 5 initial proposed rim designs

The designs, were labelled proto 1-5:

- Proto 1 – narrower tyre sidewall, large radius rim sidewall, small radius spoke bed
- Proto 2 – narrower tyre sidewall, small radius rim sidewall, large radius spoke bed
- Proto 3 – wider tyre sidewall, large radius rim sidewall, large radius spoke bed
- Proto 4 – wider tyre sidewall, intermediate radius rim sidewall, large radius spoke bed
- Proto 5 – wider tyre sidewall, smaller radius tyre sidewall, very large radius spoke bed

4. Patent pending LIMITLESS technology

After creation of the initial designs, it was clear that the optimum aerodynamic shape, with a large external rim width close to the tyre interface, would require a large amount of additional material between the inner and outer rim surface. Adding this amount of material would yield a wheelset mass that would not be acceptable for road racing.

A technology was created using a low density expanded polymer, which can be co-moulded into a recess moulded in the widest part of the rim. The polymer reduces the mass of the rim while providing additional strength to the carbon fibre structure. After considering several options a polymer was selected with the desired density, water resistance, strength and compliance to perform well when moulded into the side of a carbon fibre rim. The polymer has a density of $0.7gcm^{-3}$, compared to approximately $1.6gcm^{-3}$ for the carbon fibre/epoxy resin composite used in the rest of the rim structure. This allows a mass saving of up to 100g per wheelset. The design maintains the same thickness of carbon fibre composite in all the key structural areas when compared to a traditional rim design.

This technology is currently patent pending worldwide. Without its use, is not possible to create the rims shapes used in testing without a significant mass increase and resulting performance penalty.

5. Testing method

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.
3. Computational fluid dynamics (CFD) – uses a finite element analysis to compute the airflow through a 'mesh' constructed around a computer generated model of the shape. The time and cost required to develop detailed meshes for use with a complex and rotating component like a complete wheel makes it impractical for wheel development. Results from CFD are highly dependent on the quality of the model and mesh and need to be corroborated with other testing methods.

It was decided to test the wheels using the windtunnel at GST in Immenstaad, Germany. GST is an open wind tunnel, constructed in 1986 for use by Airbus Defence and Space. 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 Magazin for their independent aerodynamic testing.

5.1 Bicycle and component set up

Wheelsets were tested while fitted to a Canyon Aeroad Disc road bike and fitted with SRAM 140mm centreline disc rotors. A wide variety of tyres were tested during the prototype testing phase, and for final results the wheels were tested using four different tubeless tyre options representing the most popular tubeless ready 25mm and 28mm tyres on the market:

- Schwalbe Pro-One 28mm
- Schwalbe Pro-One 25mm
- Continental GP5000 28mm
- Continental GP5000 25mm

Each tyre had the mould flashings removed with sandpaper before testing, and the same individual tyre was used to test all the wheelsets.

From previous testing it was known that most of the aerodynamic difference between rim designs resulted from the front wheel since the rear wheel is largely shielded from the airflow which has also been disturbed as it passes over the bike and rider. To reduce the time taken to swap components between tests, test runs are carried out using an ENVE AR 4.5 as a standard rear wheel fitted with a Schwalbe Pro-One 28mm tyre.

5.2 Testing procedure

The testing procedure was selected to replicate the most common parameters used across the bicycle industry. The bike was mounted on a rotating table, fitted with front and rear rollers. For each run the wheels were driven by the rollers at 45 kmh^{-1} and air was passed through the tunnel at a constant speed of 45kmh^{-1}. The turntable was then rotated continuously through yaw angles between -20° and +20° to the oncoming airflow.

Figure 3 Photograph of the wind tunnel test setup

Before each test the tyre widths were measured at four points around the rim. Pressures were set lower than normal riding pressures in order to prevent damage to the 3D printed prototypes.

5.3 Development and testing of prototypes

3D printed rim prototypes were manufactured for the initial five designs, and then assembled with Pillar wing spokes into complete wheelsets for testing in the tunnel against each other and a range of class leading competitor wheelsets. The test results against competitor wheels can be found in section 8.1.

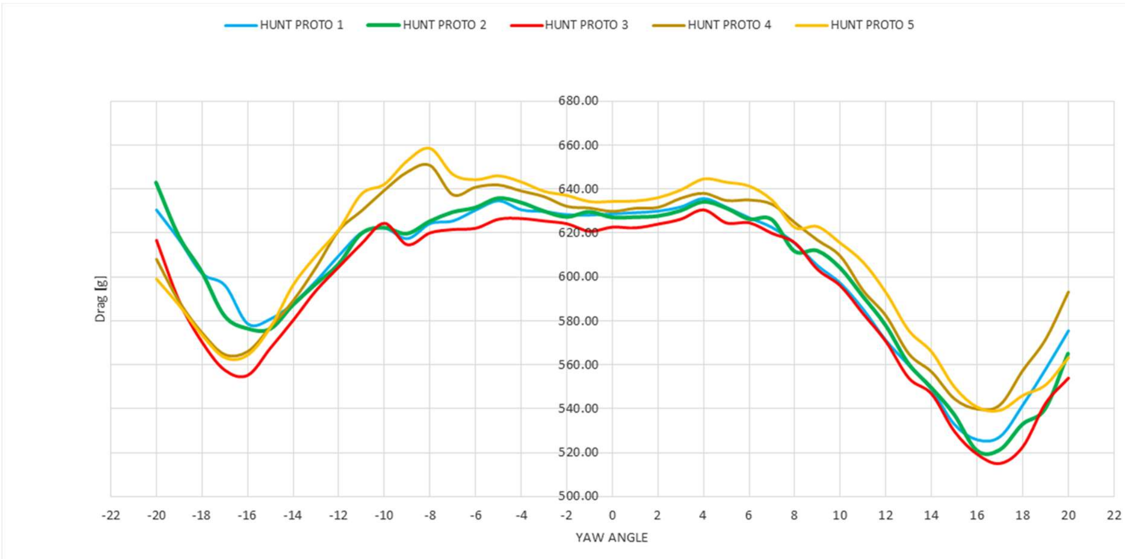

Figure 4 Drag [g] vs yaw angle [°] for all 5 HUNT prototypes

Figure 5 Photograph of the 3D printed ABS prototypes

After consideration of the performance at a range of yaw angles Proto 3 was taken forward as the best shape. It could also be seen that proto 1 and 2 performed better than proto 3 in low yaw conditions, so some elements of the proto one design were incorporated into two new designs Proto 3 revA and Proto 3 revB with slight changes to the tyre sidewall shape.

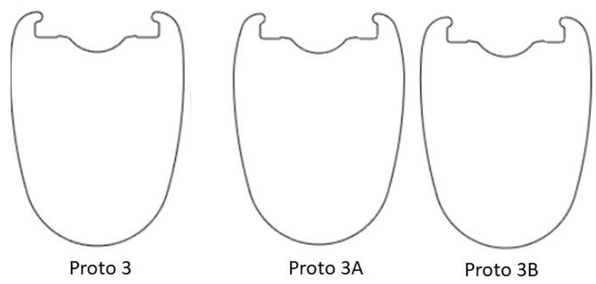

Figure 6 Cross section of the original Proto 3 and new Proto 3 revA and Proto 3 revB rim shapes

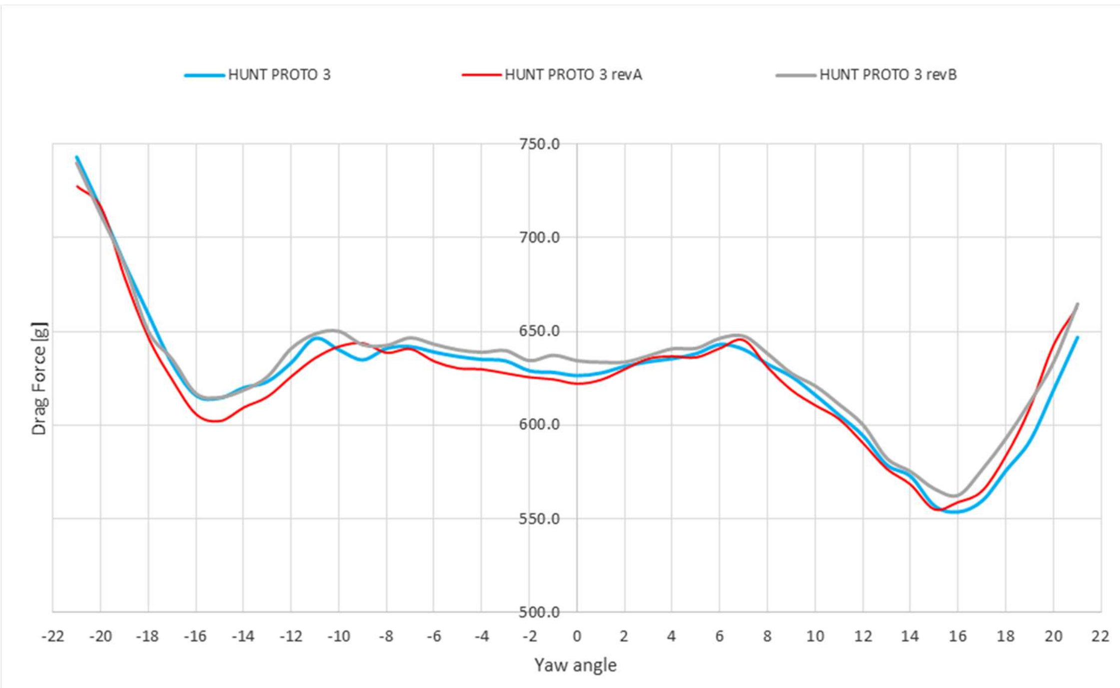

Figure 7 Drag [g] vs yaw angle [°] for Proto 3 and new revisions

Proto 3 revA gave the best performance overall and was used as the basis for the final HUNT LIMITLESS 48 AERO DISC rim design.

6. The final design

The final design from Proto 3 revA was carried forward into the production model. Final pre-production prototypes were then tested against competitor wheels to confirm the results from the prototype testing. The finished wheelsets were assembled with HUNT Sprint Hubs, Ceramic Speed bearings, Pillar external alloy nipples and Pillar Wing Spokes in a 20 spoke front, 24 spoke rear 2-cross configuration.

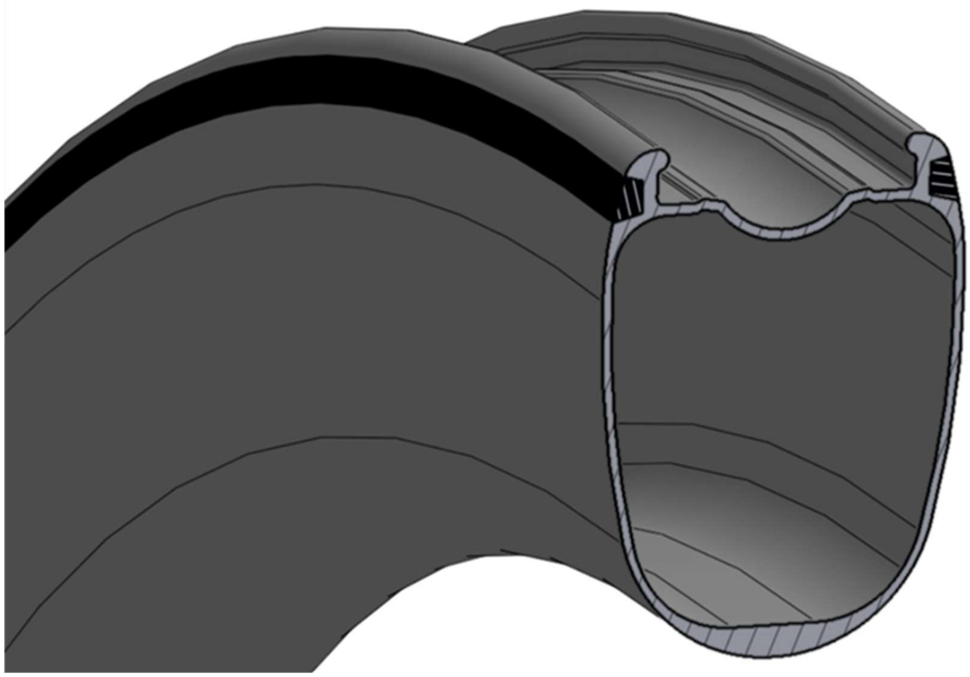

Figure 8 3D model of the final rim shape showing the areas formed from carbon fibre composite (Grey) and low density expanded polymer (Black)

7. Analysis of results

7.1 Yaw angles

A key factor in aerodynamic performance of bicycle wheels is how they perform not only when travelling straight on into the wind, but their performance when riding into a cross wind. When riding in real world conditions the wind approaches the rider from a given angle, α. When the vector of the bicycles velocity, Vb, is added to the vector of the wind, w, the rider experiences wind at the yaw angle, β.

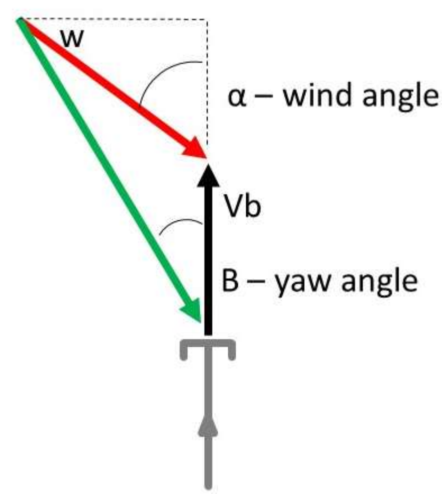

Figure 9 Diagram showing the relationship between rider velocity, Vb, wind velocity, w, wind angle, α, and yaw angle, β.

When running the test in the wind tunnel, the bike is held stationary so the yaw angle β is simply the angle the bike makes to the oncoming airflow.

7.2 Wind averaged power / wind averaged drag

Methods for making an absolute ranking of the aerodynamic performance of bicycle wheels are an area of debate in the industry, however it is widely accepted that the performance of wheels should be considered at a range of wind yaw angles. To do so quantitatively requires calculation of a weighted average of drag or power based on the relative time a cyclist may experience wind at a particular yaw angle while riding. This process is referred to as calculating a wind averaged power or wind averaged drag.

In order to allow the best comparison of our data with those of other wheel companies yaw angle weightings have been calculated using the 'ponderation law' proposed by Mavic [5]. This was produced using a bike mounted sensor on a time trial bike in a variety of locations.

The Mavic distribution is shown below. The 22.5° and 25° points have been omitted in our calculation because the windtunnel turntable allows data collection only up to 20°. However the trends from the recordings made strongly suggest that the HUNT 48 LIMITLESS AERO DISC would continue to outperform competitors at these higher yaw angles.

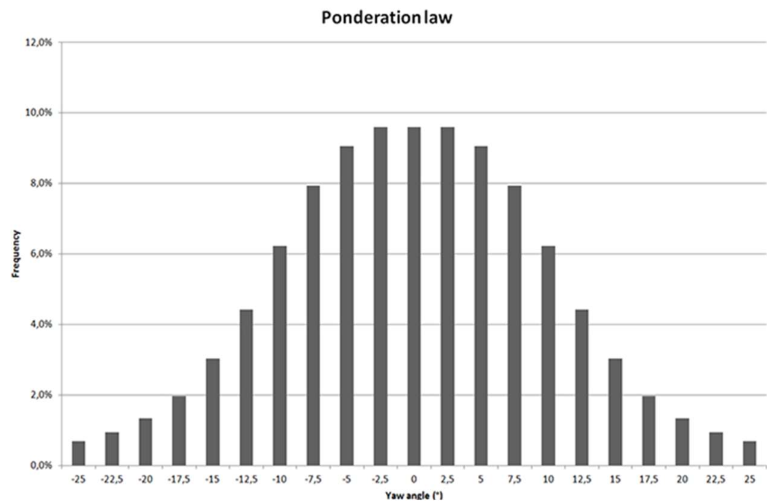

Figure 10 Yaw angle distribution proposed by Mavic, after carrying out measurements on a time trial bike with a bike mounted wind sensor.

The authors have considered an alternative approach to calculating yaw angle weightings. This uses a mathematical model where rider speed and average wind can be adjusted to create a predicted yaw angle distribution. This model and its implications are discussed further in the appendix.

8. Testing results

Throughout the development process wheels were tested against class leading competitors. Not all competitor products were readily available for all tests, and generally only best performing wheelsets were retested against the final pre-production versions of the HUNT LIMITLESS 48 AERO DISC.

It should be noted that results cannot be directly compared between tests carried out on different visits to the tunnel. Variations in air pressure, temperature, humidity and minor variations in the precise bike set up will result in different absolute values for the same test wheelset. However the relative performance between wheelsets will remain consistent.

The full testing results are shown in the tables and charts on subsequent pages.

8.1 First wind tunnel test – January 2018

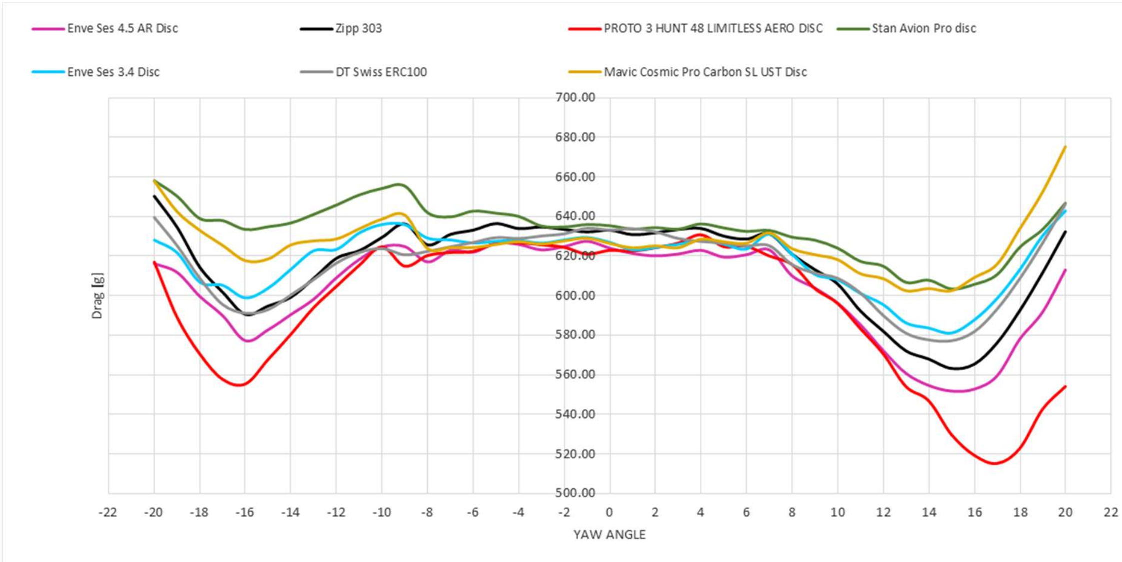

Figure 11 Drag [g] vs yaw angle [°] from first wind tunnel test January 2018 showing PROTO 3 HUNT LIMITLESS 48 AERO DISC against competitor wheelsets using a Schwalbe Pro One 28mm tyre

Configuration **With Pro One 28**	**Measured Tire width**	**Mavic calc WAD Power [Watt] @45km/h**	**Power difference [Watt]**
PROTO 3 HUNT 48 LIMITLESS AERO DISC	30.8 - 30.7	74.71	0.00
Enve Ses 4.5 AR Disc	31.5 - 31.5	75.14	0.43
DT Swiss ERC100	28.95 - 28.5	76.18	1.47
Zipp 30PP 303, ENVE SES 4.5 AR Disc, Schwalbe Pro One 28	30.6 - 30.1	76.34	1.63
Stan Avion Pro disc	27.1 - 26.8	77.87	3.15
Enve Ses 3.4 Disc	30.6 - 30.2	76.26	1.55
Mavic Cosmic Pro Carbon SL UST Disc	29.3 - 29.2	76.76	2.05

8.2 Second wind tunnel test – April 2018

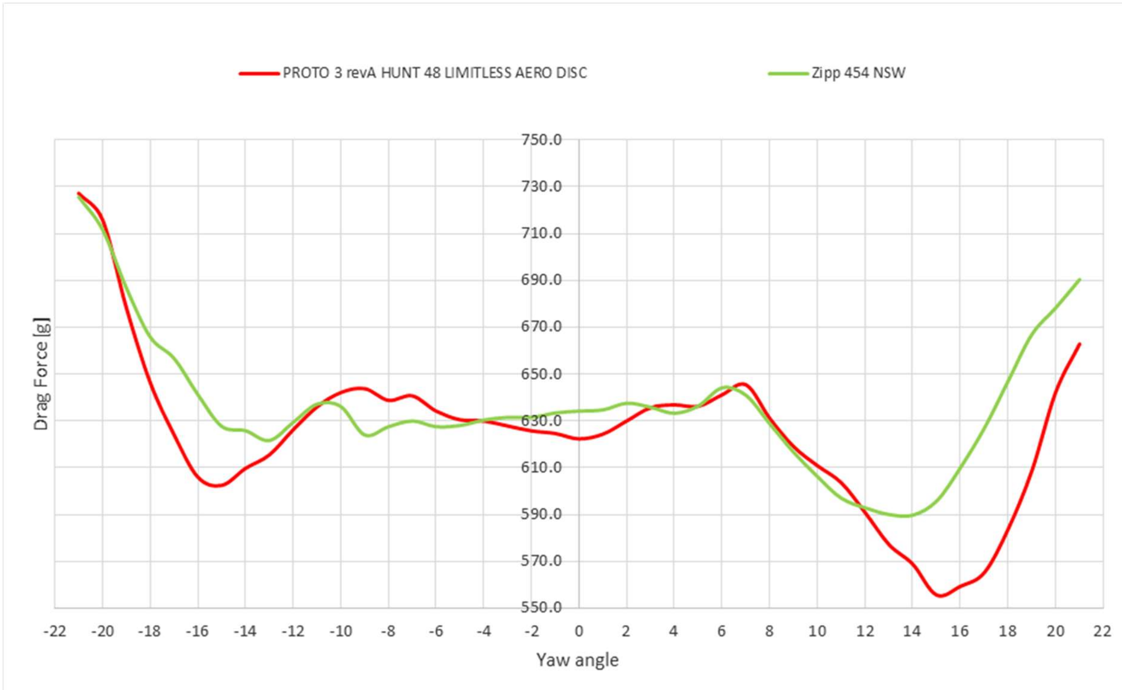

Figure 12 Figure 1 Drag [g] vs yaw angle [°] from second wind tunnel test April 2018 showing PROTO 3 rev A HUNT LIMITLESS 48 AERO DISC against Zipp 454 NSW using a Shwalbe Pro One 28mm tyre

Configuration **With Pro One 28**	**Measured Tire width**	**Mavic calc WAD Power [Watt] @45km/h**	**Power difference [Watt]**
PROTO 3 revA HUNT 48 LIMITLESS AERO DISC	30.2-30.1	76.74	0.00
ZIPP 454 NSW	27.35-27.25	77.37	0.63

8.3 Third wind tunnel tests April 2019

Tests conducted with Schwalbe Pro One 28mm:

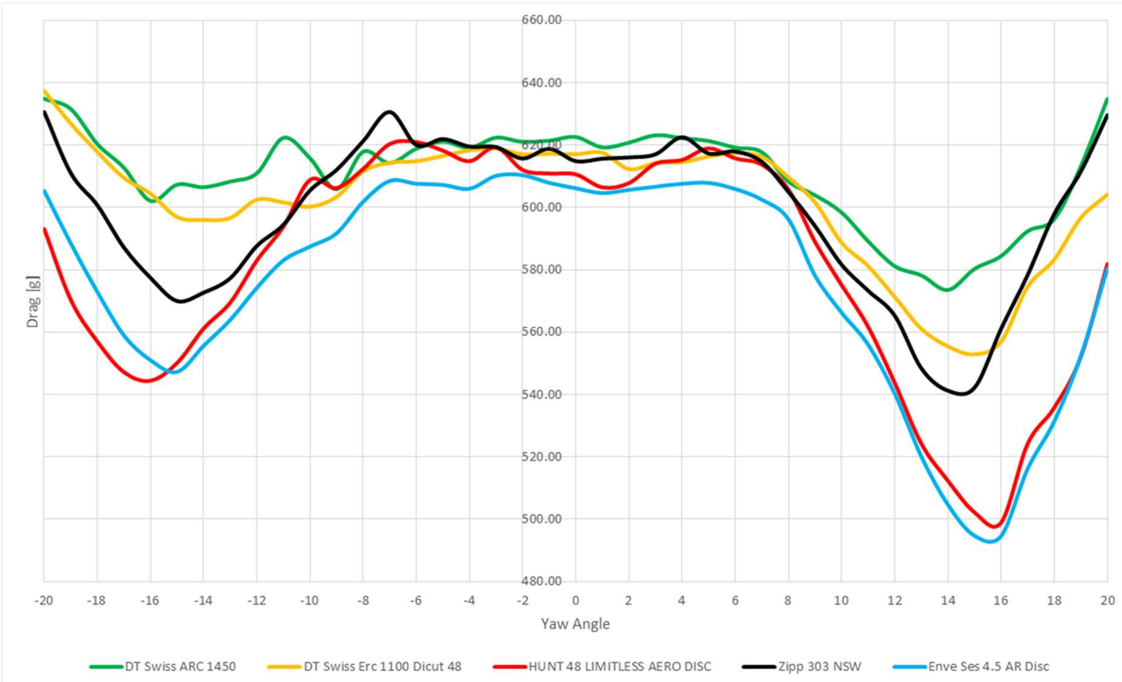

Figure 13 Drag [g] vs yaw angle [°] from third wind tunnel test in April 2019 showing HUNT 48 LIMITLESS AERO DISC against competitors, using a Schwalbe Pro One 28mm tyre

Configuration **With Pro One 28**	**Measured Tire width**	**Mavic calc WAD Power [Watt] @45km/h**	**Power difference [Watt]**
DT Swiss Arc 1450	28.3-28-28.3-28.5	75.31	2.98
DT Swiss Erc1100 Dicut 48	29.0-29.2-28.8-27.6	74.43	2.10
Zipp 303 NSW	29.8-29.6-29.7-29.3	74.87	2.54
HUNT 48 LIMITLESS AERO DISC	30.7-30.5-30.9-30.7	73.25	0.93
Enve Ses 4.5 AR*	31.6-31.3-31.7-31.0	72.33	0.00

*The Enve Ses 4.5 AR does not strictly meet the criteria for inclusion in the test as the rear wheel is 55mm deep. Nonetheless it provided an excellent benchmark for testing against the HUNT 48 LIMITLESS AERO DISC. Enve AR wheelsets have only been tested with Schwalbe Pro One 28mm tyres per the manufacturers guidance that they are not compatible with the other tyres used.

Tests conducted with Schwalbe Pro-One 25mm:
Time limitations prevented testing of all competitor wheels – Enve SES 4.5 AR not tested in accordance with Enve's recommended minimum 28mm tyre width.

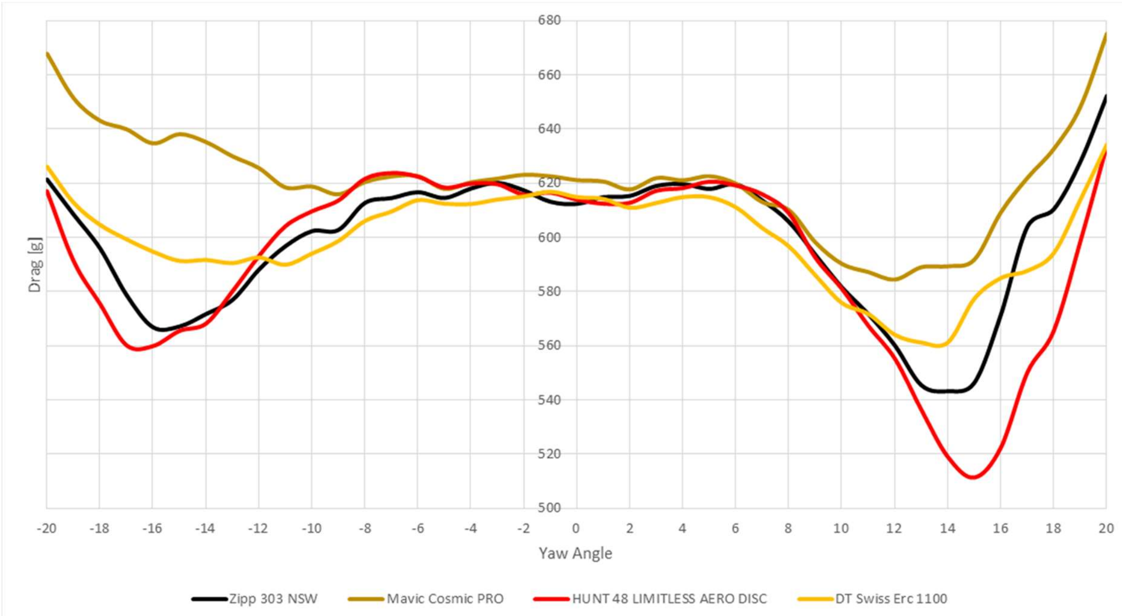

Figure 14 Drag [g] vs yaw angle [°] from third wind tunnel test in April 2019 showing HUNT 48 LIMITLESS AERO DISC against competitors, using a Schwalbe Pro One 25mm tyre

Configuration With Pro One 25	Measured Tire width	Mavic calc WAD Power [Watt] @45km/h	Power difference [Watt]
Zipp 303 NSW	27.5-27.6-27.3-27.3	74.11	0.16
Mavic Cosmic PRO Ca UST	26.7-26.9-27.4-27.3	75.81	1.86
DT Swiss ERC 1100	27.1-27.3-27.3-26.8	73.97	0.02
HUNT 48 LIMITLESS AERO DISC	28.9-28.6-28.6-29.2	73.96	1.35

Tests conducted with Continental GP 5000 TL 28mm:

Enve SES 4.5 AR not tested in accordance with Enve's guidance that this wheelset it not compatible with this tyre.

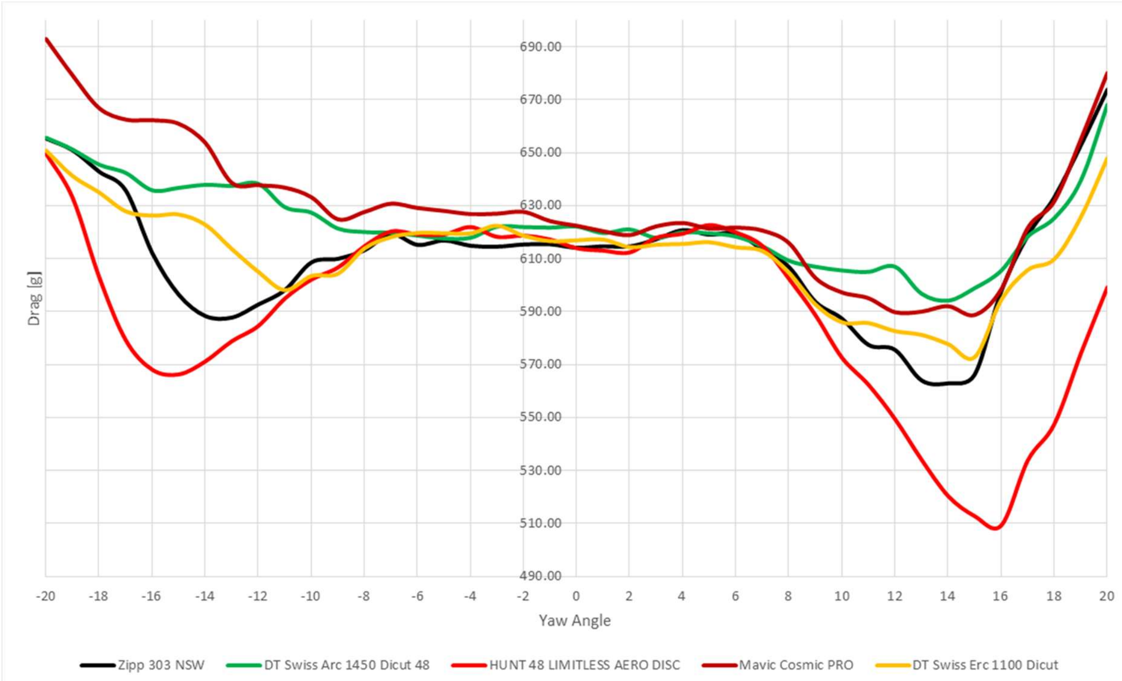

Figure 15 Drag [g] vs yaw angle [°] from third wind tunnel test in April 2019 showing HUNT 48 LIMITLESS AERO DISC against competitors, using a Continental GP5000 TL 28mm tyre

Configuration With Continental GP 5000 28	Measured Tire width	Mavic calc WAD Power [Watt] @45km/h	Power difference [Watt]
Zipp 303 NSW	29.51-29.19-29.4-29.2	74.86	1.06
DT Swiss Arc 1450 Dicut 48	27.0-27.1-27.1-27	76.14	2.34
Mavic Cosmic PRO	27.7-27.8-28-27.6	76.59	2.79
DT Swiss ERC1100 Dicut	28.1-28-27.8-27.9	75.00	1.21
HUNT 48 LIMITLESS AERO DISC	29.4-29.5-29.4-29.4	73.80	0.00

Tests conducted with Continental GP5000 TL 25mm:

Time limitations prevented testing of all competitor wheels – Enve SES 4.5 AR not tested in accordance with Enve's recommended minimum 28mm tyre width.

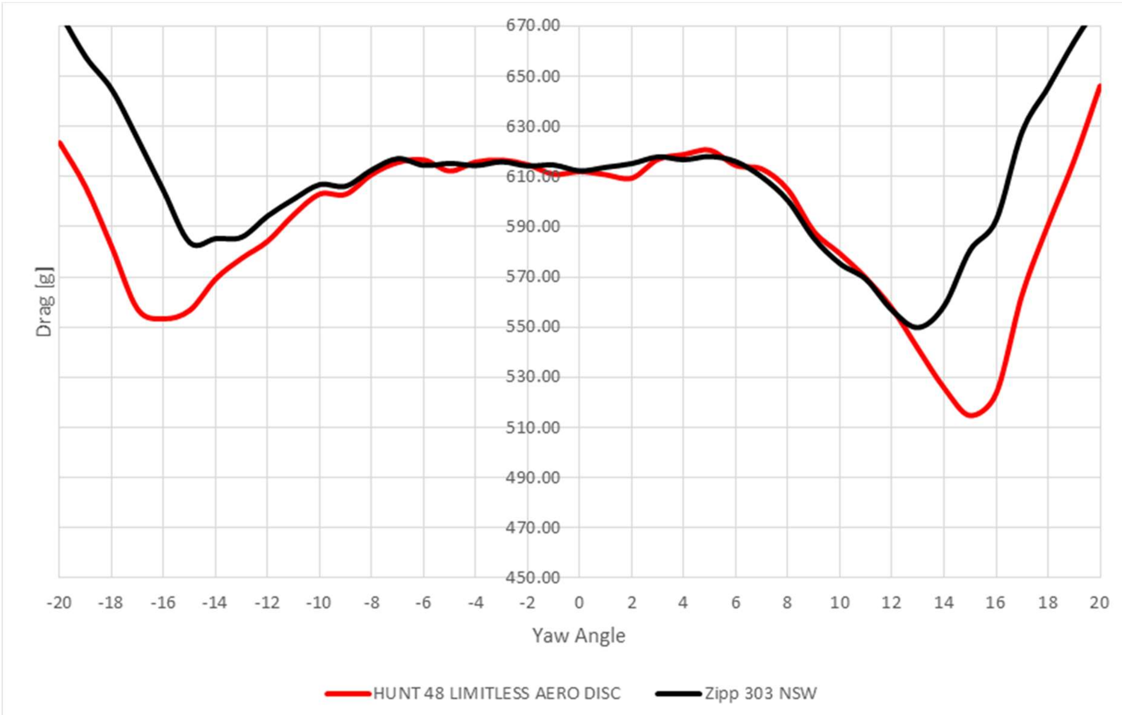

Figure 16 Drag [g] vs yaw angle [°] from third wind tunnel test in April 2019 showing HUNT 48 LIMITLESS AERO DISC against competitors, using a Continental GP 5000 TL 25mm tyre

8.4 Fourth wind tunnel test - June 2019

The Enve Ses AR 3.4 Disc wheelset was released in May 2019 – an additional test for this wheelset was arranged. In order to complete the test in a timely manner the tests were carried with the front wheels only, mounted on a single wheel turntable and roller, with no bike. Note that the total drag and power values are lower without the presence of a bike.

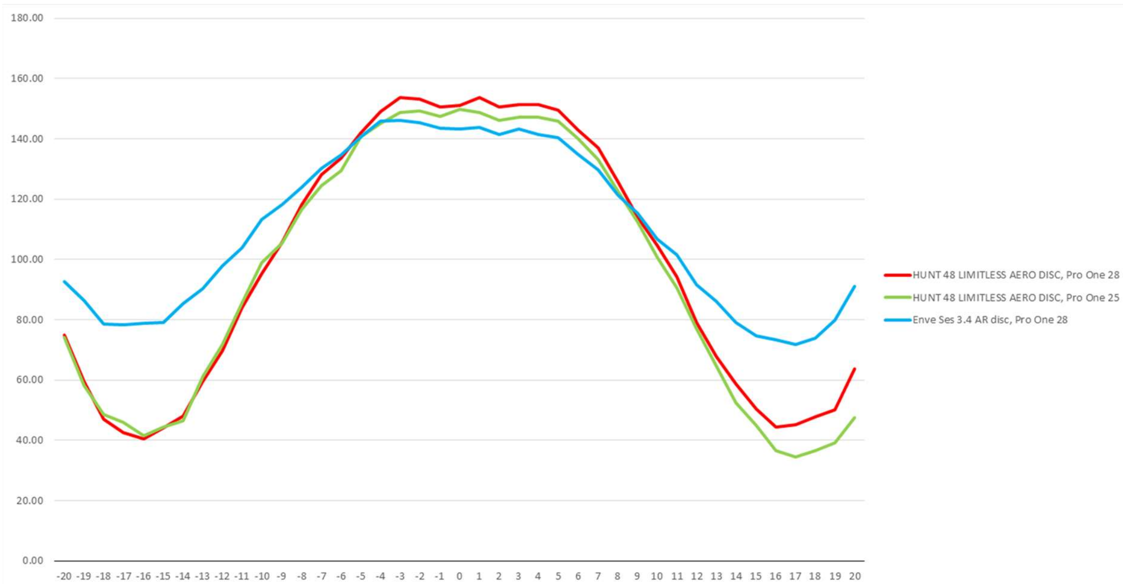

Figure 17 Drag [g] vs yaw angle [°] from third wind tunnel test in April 2019 showing HUNT 48 LIMITLESS AERO DISC against Enve SES AR3.4, using a variety of tyres

Configuration	Mavic Calc WAD Power [Watt] @45km/h	Power difference [Watt]
HUNT 48 LIMITLESS AERO DISC, Pro One 28	14.49	0.26
Enve Ses 3.4 AR disc, Pro One 28	14.87	0.63
HUNT 48 LIMITLESS AERO DISC, Pro One 25	14.24	0.00
Enve Ses 3.4 AR disc, Pro One 25 – Not compatible	-	-

9. Conclusions

The HUNT LIMITLESS 48 AERO DISC wheels have been tested extensively in the wind tunnel with data showing that they have a better aerodynamic performance than all other wheelsets tested up to and including 50mm in depth.

The power data from the tunnel was analysed with a set of yaw angle weightings independently published by Mavic and shows that the wind averaged power performance exceeds all of the other wheels tested against either the final HUNT LIMITLESS 48 AERO DISC wheelset, or the slightly less aerodynamic HUNT Proto 3 and Proto 3A versions.

The development and testing process has shown the particular benefit of a rim shape where the external width of the rim exceeds the width of the tyre, especially at higher yaw angles, which are experienced more frequently by drop bar road racers and other real world riders. The use of the patent pending LIMITLESS technology allows these aerodynamically beneficial wider shapes to be manufactured without increasing the rim mass significantly over a traditional rim construction method.

10. Further work

The LIMITLESS technology will be applied to other rim depths to provide a wider range of wheel options suitable for different racing styles and wind conditions, providing even more benefits to riders.

Further work will be carried out on yaw angle analysis to propose a new wind averaged power weighting, available to all cycling companies, which is more representative of the wind conditions experienced in drop bar road racing and riding.

Acknowledgements

Thank you to Ernst Pfeiffer at GST for all of his patience, hard work and good humour when we have been working together at the tunnel.

We would also like to thank Schwalbe for assisting us with creating our CAD models for the wheel and tyre which were essential in generating the correct rim shapes.

Thank you to all of the staff at the Rider Firm every one of whom have contributed hugely to getting this project to where it is today.

Lastly and most importantly an enormous thank you to all the dedicated and enthusiastic HUNT riders out there who have supported us, encouraged us and driven us to keep improving what we do for riders every day. Without you this project would have no purpose at all.

Appendix: A mathematical model for calculating yaw angles based on rider speed and wind speed

An initial mathematical model was created to calculate theoretical yaw angles that could be experienced by a rider at a given speed in a uniform wind. The simulation imagines a rider completing a circular route in conditions of constant wind speed and direction. This model then outputs a histogram showing the percentage of time the rider spends experiencing a given yaw angle.

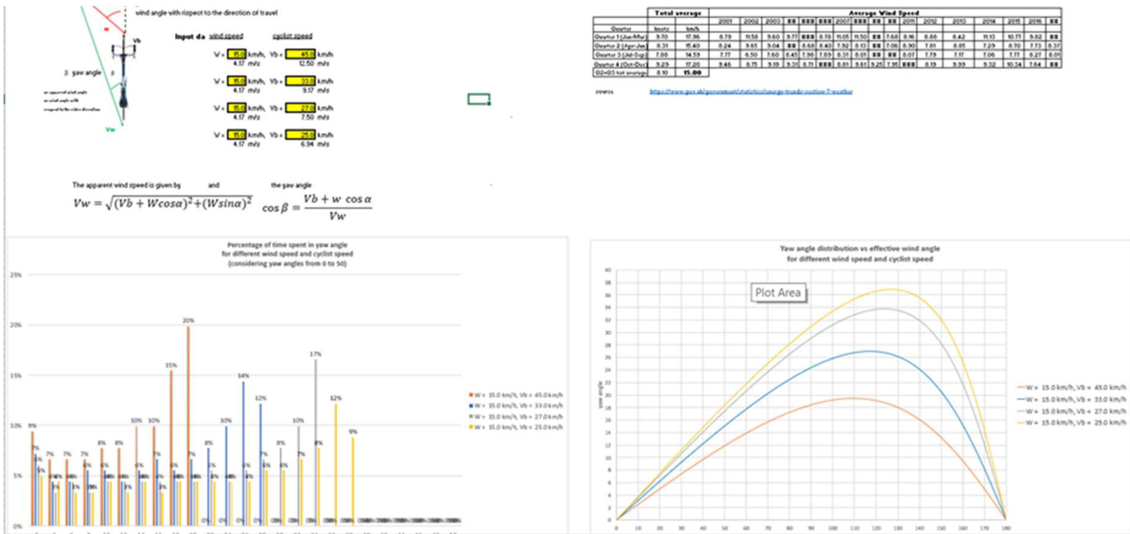

Figure 18 Screen capture showing the yaw angle model in use

An example calculation is shown below for a rider experiencing the UK average wind speed of 15km/h [6] and riding a speeds of 45, 33, 27 ad 23 km/h.

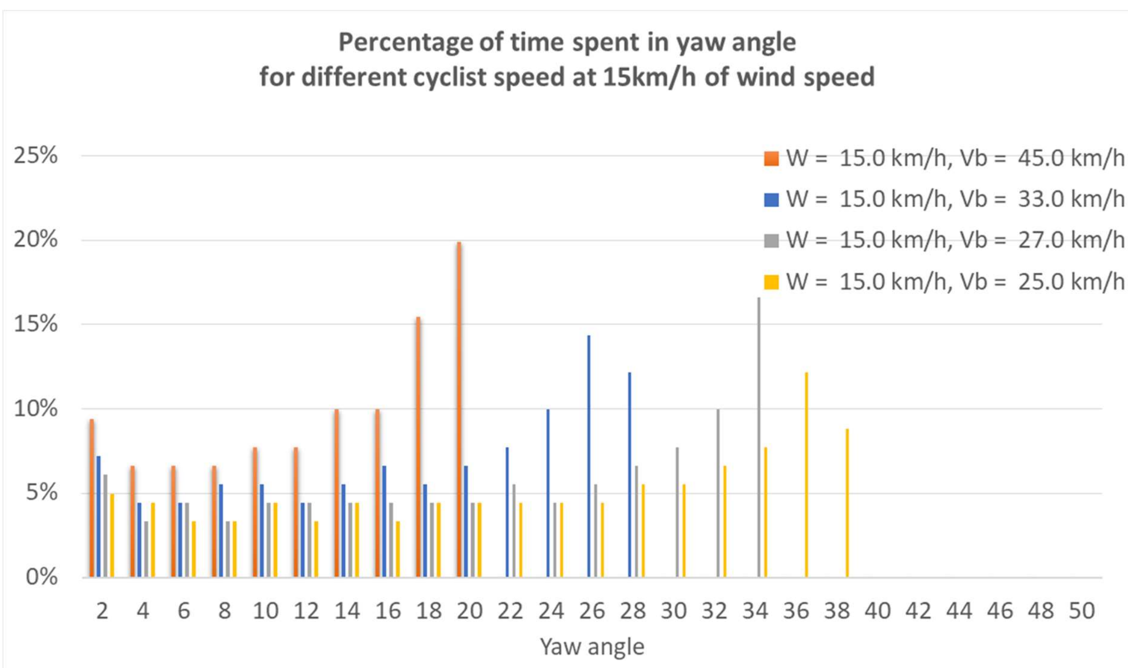

Figure 19 Theoretical distributions of yaw angles based on a circular path at different uniform wind conditions

Albeit simplified, these theoretical calculations show that the true yaw angles experienced even by professional time triallists riding at speeds of 45km/h or more may be significantly more than other models suggest. As speeds are reduced when riding on a drop bar bike or at amateur levels these yaw angles increase even further.

Further study is planed in this area, with the possibility of establishing an accepted standard for aerodynamic testing that is more representative of drop bar road racing and riding in real world conditions.

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