The HUNT SUB50 LIMITLESS AERO DISC: Designing and testing the world's most aerodynamic disc brake wheelset up to 50mm depth.

Patrick Brown M.Eng, John Marchment C.Eng, MIMMM
HUNT BIKE WHEELS (ITS Cycling Limited), West Sussex, United Kingdom

Wind tunnel operation and raw data collection by Ernst Pfeiffer
GST Gesellschaft für Strömungsmeßtechnik, Immenstaad, Germany

Abstract

In the late 2010s the adoption of disc brakes in professional and amateur road cycling 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. During the development of the HUNT 48 Limitless Aero Disc (48LAD) the HUNT engineering team took full advantage of this to create the world's fastest road disc brake wheelset up to 50mm in depth.

In this paper the authors set out to improve on the performance of the 48LAD creating a highly aerodynamic road race specific wheelset, optimized around the wider 28mm and 30mm tyres that have become the default choice in the professional peloton.

In the course of development, the team managed to improve the aerodynamics of the previous 48LAD wheelset reducing drag by 1.4W whilst also reducing its weight by over 130g to 1378g

The completed SUB50 rim profile wheelset was tested against a range of the world's leading wheelsets at approximately 50mm rim depth, using the wind averaged power analysis proposed by Mavic. It proved to be one of the three most aerodynamic wheels tested, with the two wheelsets showing lower drag each having larger rim depths and greater mass than the SUB50.

1.0 Introduction – Technical background and history

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 use – since larger rim 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 Developments in road racing technology – near universal adoption of disc brakes, wider tyres, and tubeless technology

In 2016 cycling's governing body the UCI began trialing the use of disc brakes in road cycling. This technology became fully authorised in 2018. Since then, there has been significant development in both wheel and bicycle designs to maximise the aerodynamic performance of disc brake bikes. For wheel design this has primarily been by taking advantage of the additional flexibility in rim shape and width that is possible without having to use the rim as a braking surface or having to fit into a rim brake caliper. For bike design, the disc brake calipers can be placed behind frame structures and great flexibility in design is available for the fork and seat stays as they are no longer required to mount a caliper.

During this period there has also been a near universal acceptance of the benefits of using wider tyres and tubeless set-ups. The majority of professional teams are now running 28 or 30mm tubeless tyres in most of their road racing calendar. Almost all of the leading racing tyre models are now supplied primarily in a tubeless-ready set up. [1] [2]

As well as enhanced grip from running wider tyres at lower pressures and the puncture prevention benefits of using a tubeless set up, studies show that these technologies can lower rolling resistance by reducing the deformation of the tyre, and reducing vibrational losses in the bike and rider system.[3] Tubeless set ups can also reduce rolling resistance as there is no friction generated by the movement of and inner tube against the tyre – a feature present both in tubular and tubed clincher set ups.[4]

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.

1.2 Specific wheel developments since the development of the 48LAD

In 2021 HUNT partnered with the Qhubeka Assos world tour team – providing the 48LAD wheels to the team which were raced to a Giro d'Italia stage win in 2022 as well as a top-10 placing at Paris-Roubaix.

Following the launch of the 48LAD other wheel manufacturers used similar design concepts and a number of new wheelsets came onto the market with wider rims. The Roval Rapide from Specialized in particular managed to achieve a slight aerodynamic advantage over the 48LAD, a wheelset which also used a different profile for front and rear wheels. Vision and Enve also widened the external width of their wheel ranges to 32mm and above.

Across the industry there has also been a move to the use of hookless rim profiles with some potential aerodynamic and weight reduction benefits. When fitted to a hookless rim tyres typically have a more upright shape, as opposed to the 'light bulb' shape that can be created with a hooked rim. There is also a less pronounced recess where the rim meets the tyre – both of which smooth the transition of air from the tyre to the rim.

HUNT have access to carbon spoke technologies utilised at world tour level by supported athletes and this is the same system provided by other wheel companies supplying world tour teams. As the carbon spoked wheels have proved to be more laterally responsive and lighter, most of the development work and testing present in this paper is based on wheels built with carbon spokes.

2.0 Overview of testing and development tools

HUNT have responded to this by initiating a new design project utilising Computational Fluid Dynamic (CFD) techniques. The 48LAD was an empirical design which was validated by producing a number of 3D printed rims to test in the wind tunnel. Further validation was carried out on the finalised production rim.

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. 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.

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 (eg 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 decided to test the 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 authors present in this paper how this process resulted in the performance improvements, additional background information on CFD use can be found here in our CFD Explainer [5].

The aim of this project was to improve the aerodynamic performance and at the same time reduce the weight of the previous 48LAD. The project also aimed to assess the potential benefits of different front and rear profiles. 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 the majority 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. Additionally, with the wide profiles possible by using HUNT's patented Limitless technology, the stall point can be pushed to higher yaw angles improving handling on the front wheel and reducing the need for a lower depth front rim.

In order to give the greatest freedom in design to achieve the goals of aerodynamic performance, weight, and handling the project was free to explore different front and rear rim depths and designs.

2.1 Wind averaged drag

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. In order to give a consistent method for combining these yaw angles into a single wind averaged drag (WAD) value Mavic has developed and published a 'ponderation law'.

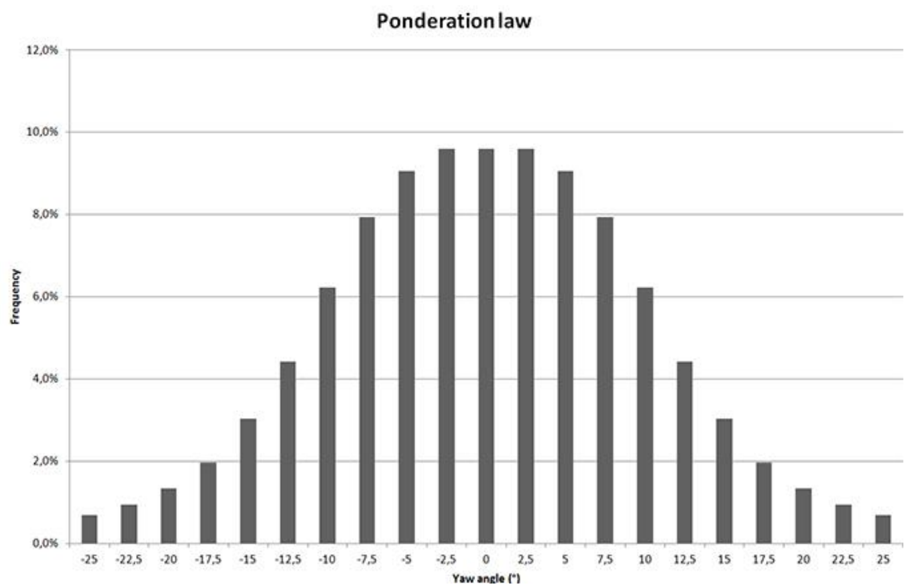

Figure 1- Mavic chart showing their assessment of time spent by riders experiencing different yaw angles.

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

3.0 The purpose of the wheels

The overall purpose of the wheels is to be the fastest all-round road racing wheelset available, combining leading aerodynamic performance, low mass and good cross-wind stability. In order to achieve this the team established a design brief for the project:

- A mid-depth wheelset specifically designed for mass-start road race use.
- Optimised for the best aerodynamic performance with wider 28 and 30 mm tyres.
- A hookless rim design to reduce rim weight, improve aerodynamics, and create the potential to improve the sustainability of the manufacturing process by removing the need for single use disposable rim bed inserts.
- A tyre bed design compliant with the latest ETRTO tubeless standards
- Key dimensions for the wheelset were determined:

- The rim depth was set at less than 50mm 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 23mm providing a stable tyre profile with a wide base whilst still ensuring a safe and secure tyre fit and compatibility under the latest ETRTO standards for new rim development with 28mm tyres. (Some wider internal rim width designs were also explored)
- Importantly the external rim width was not specified at this point – the design was left open to develop whatever shape would be most beneficial.

4.0 CFD process

The initial development of the rim shapes was conducted using computation fluid dynamics (CFD) techniques carried out by HUNT's in-house engineering team a total of 42 different profiles. This CFD model and the resulting design proposals would later be 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 Aero Disc 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 were 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.

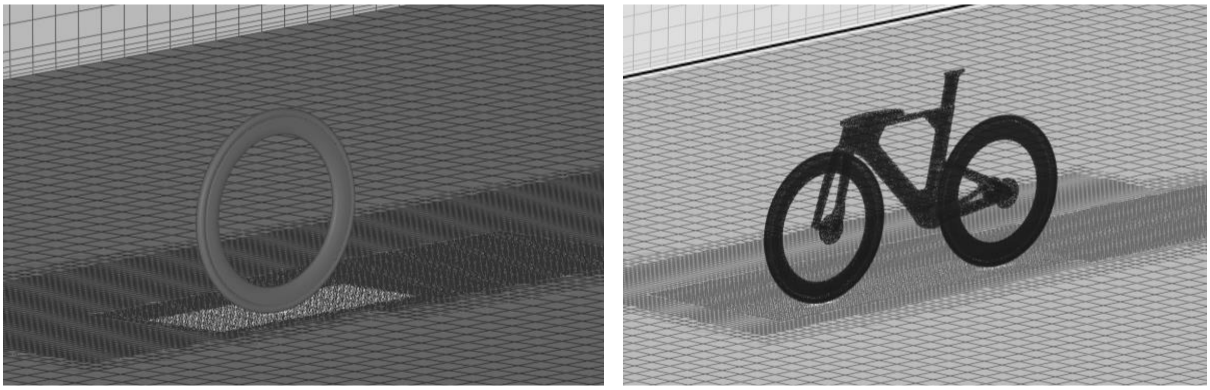

Figure 2- Example images of wheel only and bike simulation.

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.

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 of the detail of the tyre, wheel components and the complete bike will input into the final selection of the best design and comparison to competitors.

4.1 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.

4.2 CFD Methodology – Complete Bike

After shortlisting the best performing designs these were analysed with the complete bike model, using a bike design based on the Argon18 E119+; previous CFD simulations have been run with this bike providing a good understanding of the model's reliability with this geometry and mesh.

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 was the primary development tool.

Again, here it was decided to focus on positive yaw angles on the non-drive side in order to make the most efficient use of computing resources, along with the simplifications already mentioned 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.

6.0 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.

6.1 HUNT SUB50 Front profile

6.1.1 Initial CFD Development

In the initial development stages, no parameters were fixed, with the objectives of creating a very aerodynamically efficient profile while maintaining high levels of aero stability.

The first simulation runs were 48 mm deep so that it could be compared to the 48LAD, as this is a profile for which the most data is available.

The initial tests on the front wheel were run as wheel-only simulations allowing simulations to be run for a similar quantity of computational resources whilst still gathering useful results as modern bikes with wide fork blades lead to minimal interaction between the wheel and fork. Predominantly a 28 mm tyre was used with shape provided by Schwalbe representing their Pro One tyre.

The profiles were tested from 0° to 16° yaw angle as this is normally enough for the profile to stall. This also covers the yaw angles that riders will encounter most often.

The initial test runs were to find which parameters had the most effect on the aerodynamic drag and to test a range of geometries with only one parameter being changed. The initial parameters were: shoulder width, rim depth, rim width and, nose radius.

Typical simulation runs were 30 per rim design and CFD run times of 12,000 hours for each rim.

6.1.2 Shoulder width

The original 48LAD sits at 30.9 mm at the shoulder. Wider shoulders was a feature that the authors expected to have the most potential for a substantial gain in performance.

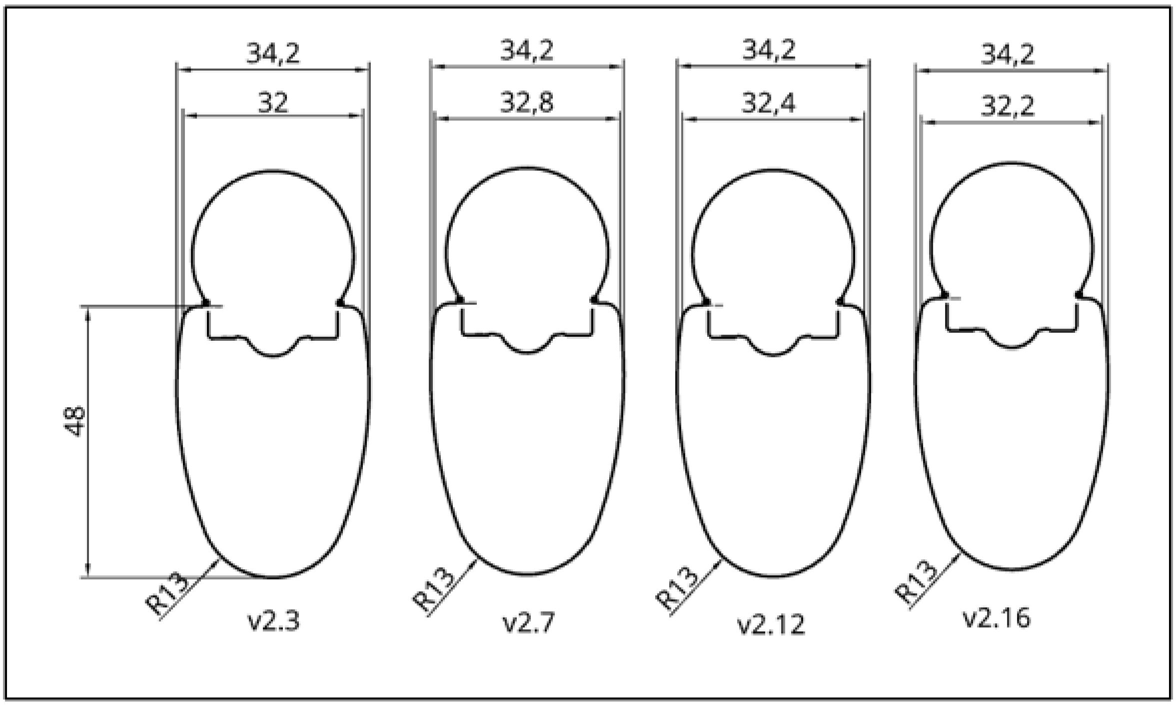

Figure 3 – Cross-sections showing a range of rims with different shoulder widths that were simulated.

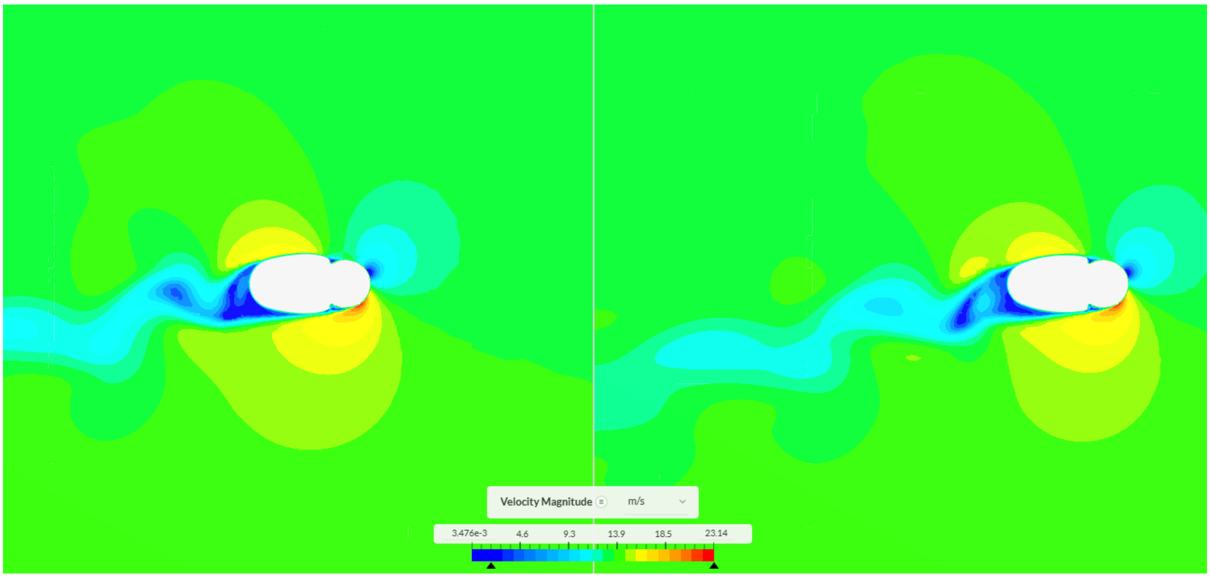

Figure 4 - Visualisation of the different flow structures around the 48 limitless (left) and v2.12 (right).

The wider shoulders keep the flow on the leeward side of the wheel attached further along the profile, leading to a reduced amount of stagnation and very low velocity flow at the tail of the rim.

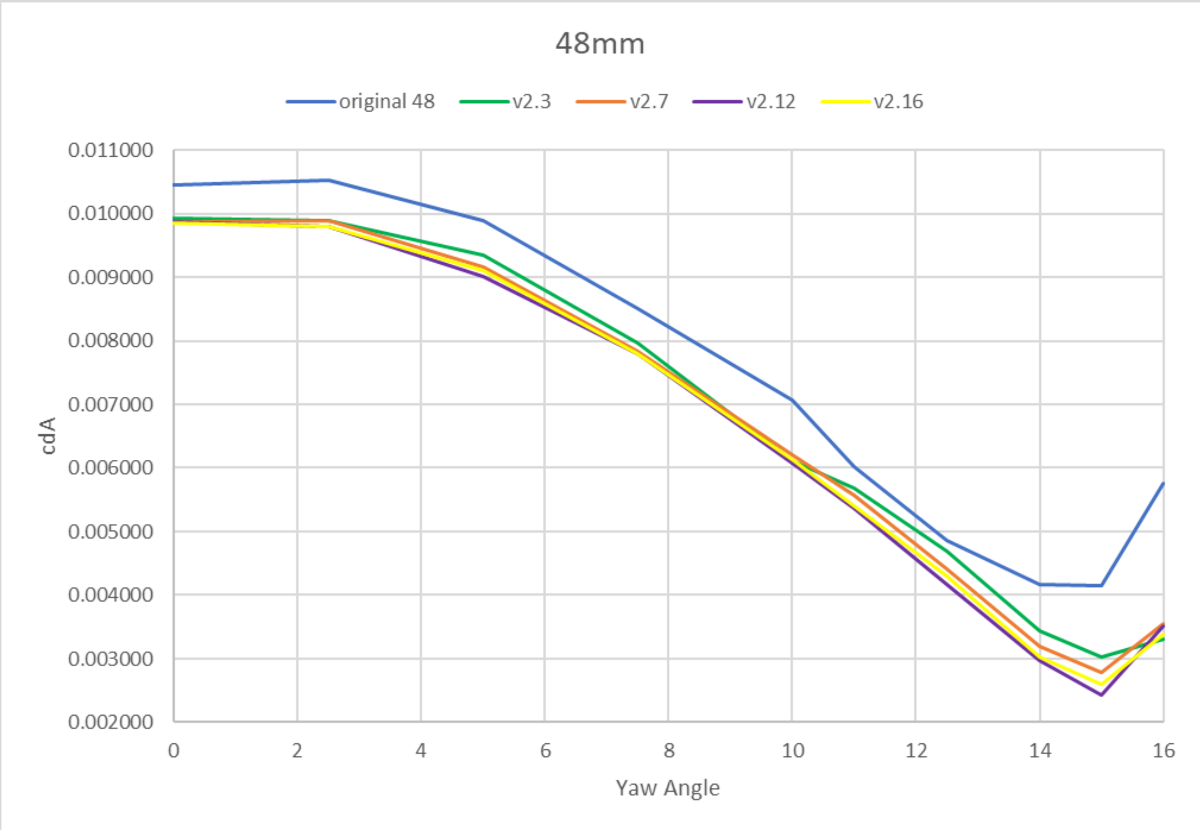

Figure 5 - Simulated wheel only drag comparison 0° - 16°, demonstrating the effect of hook width on CdA

Figure showing the different profiles performance through a range of yaw angles.

These wider tested shapes show a step change in performance of the 48LAD with the wider shoulders showing a significant gain. However, when looking at the proposed designs the optimum shoulder width was 32.4mm, offering separation from the rest of profiles at 5°yaw and then again above 12°, with the other proposed designs all performing similarly to each other.

6.1.2 Nose radius

The design of the rim 'nose' is important, as it is the last point of contact on the leading side of the wheel meaning that it plays a large part in the control of the stall condition on the trailing edge of the rim. But it is also the leading edge on the trailing side of the wheel. These two uses would ideally require different profiles, but on a wheel this is obviously not possible so a trade-off needs to be found creating a balance between the two conditions achieves the best overall performance.

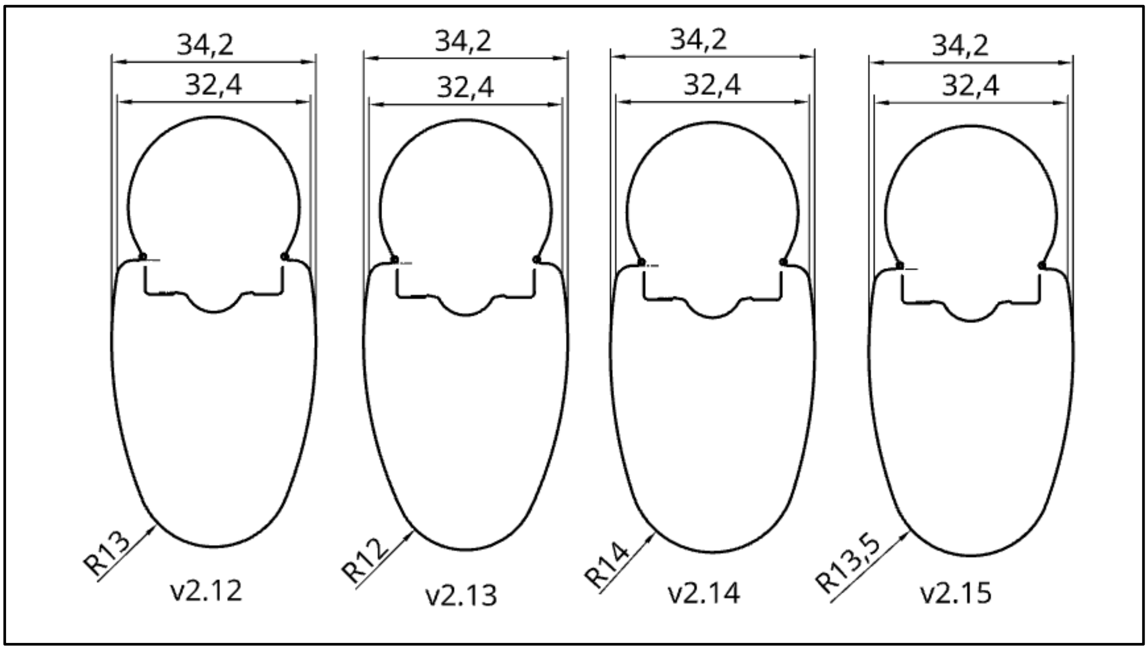

Figure 6 – Cross sections of front rim versions tested with a range of nose profiles.

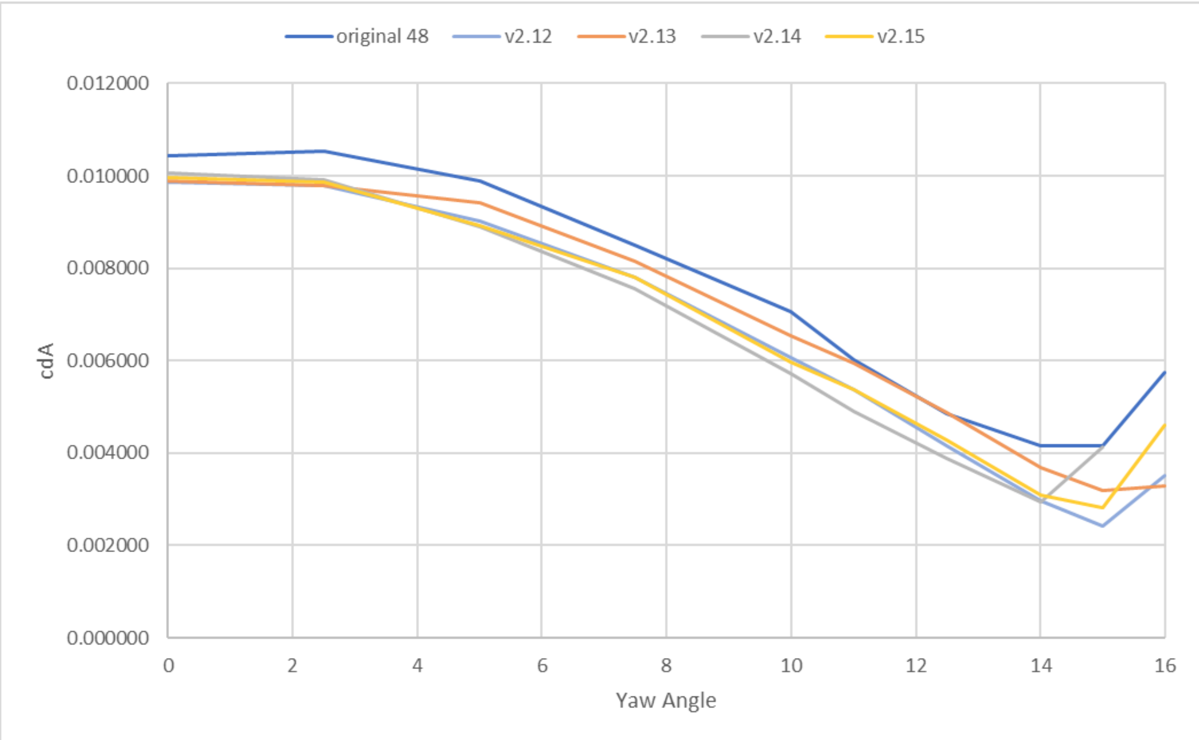

Figure 7 - Simulated wheel only drag comparison 0° - 16°, demonstrating the effect of nose radius on CdA

What is demonstrated here is that the smaller the radius is at the nose of the profile the higher the drag is until the profile stalls, while the larger nose radius causes the flows to separate earlier. The wider nose radius forces a more dramatic transition from the nose to the side wall. The nose radius of 13mm was chosen as this offered the best trade-off between low drag at low yaw angles as well as a later stall.

6.1.3 Rim Depth

Rim depth was the next parameter that was examined making the rim deeper allows less disruption to the airflow but also comes with an increase in cross sectional area which increases the side forces on the rim.

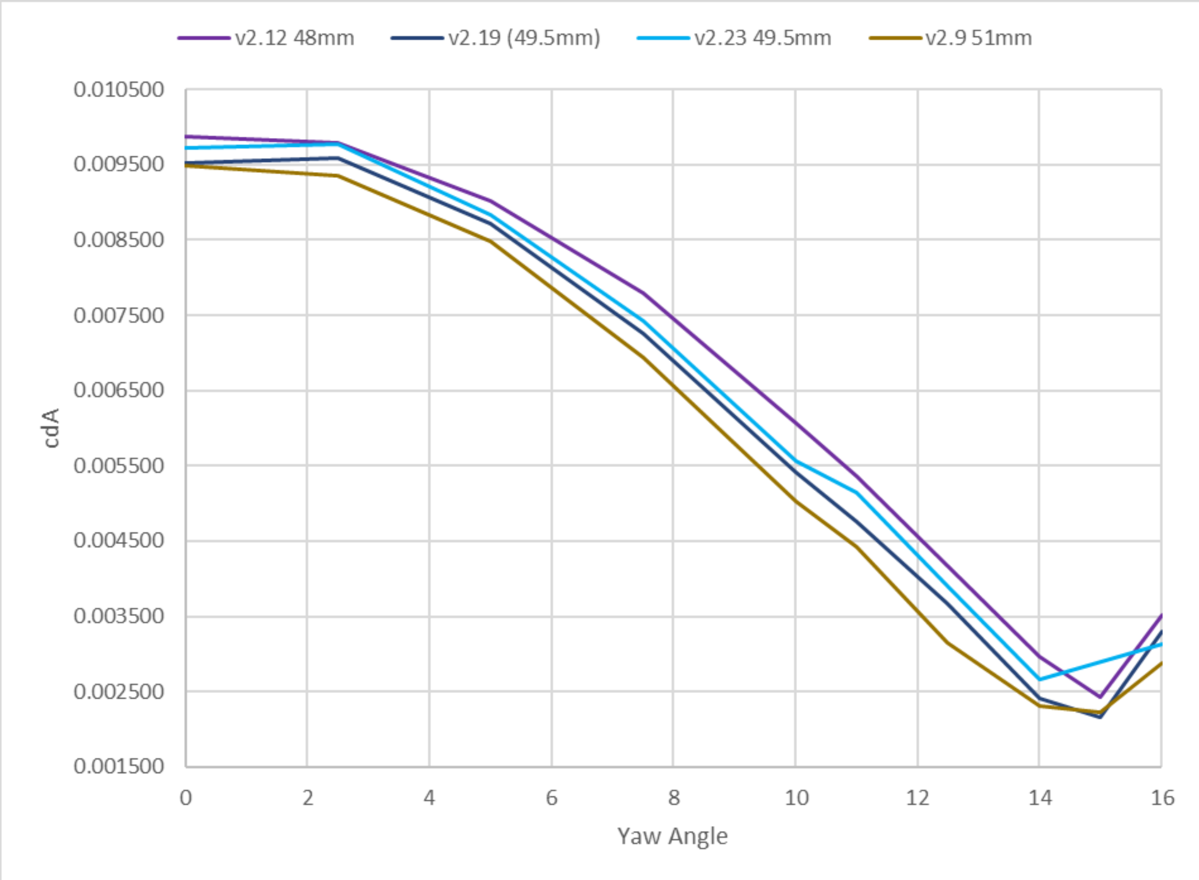

Figure 8 - Simulated wheel only drag comparison 0° - 16°, demonstrating the effect of rim depth on CdA

A big step was observed by going from v2.12 to v2.19 with the nose shape and shoulder width kept identical. For v2.23 the shoulder width was reduced from 32.4mm to 32mm while maintaining the same depth to see if this relationship changed with the change in chord length of the profile but this led to a drop in performance.

Then taking the v2.19 to 51mm while keeping the rest of the geometry identical gave another step in performance but less significant and it was deemed that it would not be worth the trade-off of reduced cross wind stability.

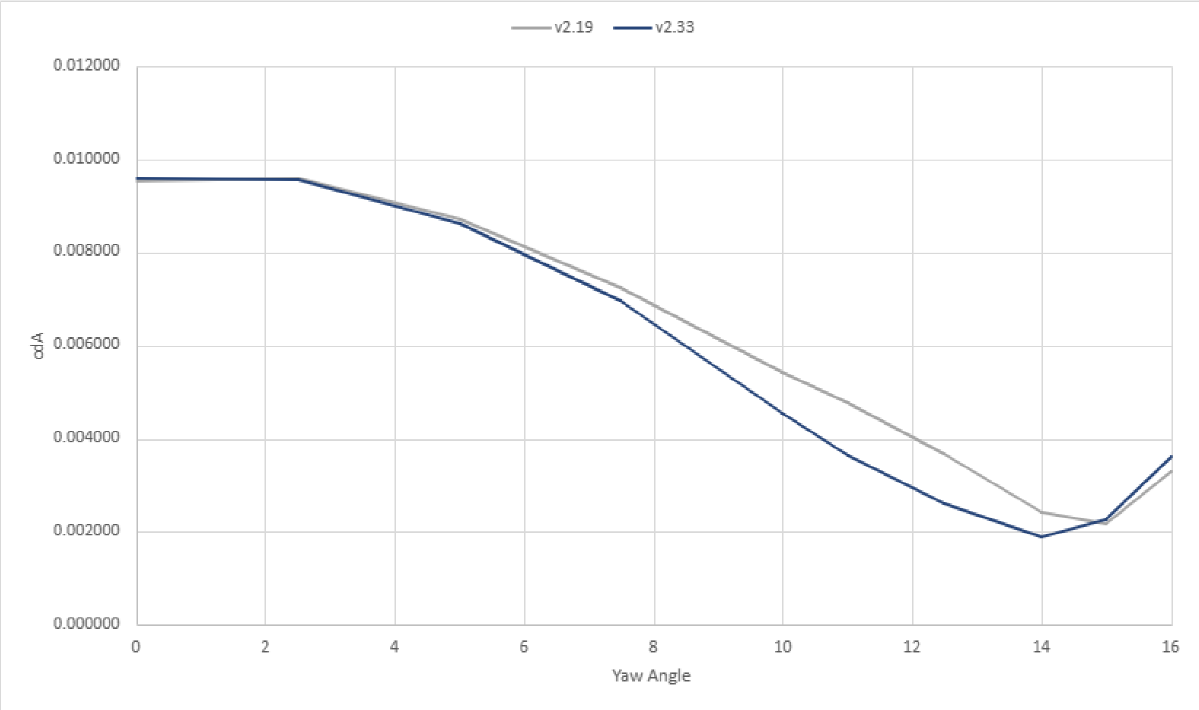

Figure 9 - Simulated wheel only drag comparison 0° - 16°, demonstrating the effect of internal rim width on CdA

For the front profiles the v2.19 mm profile was consistently the fastest external shape in both full bike simulations and in wheel-only simulations. This external profile was then tested with a different internal rim width going from 23 mm to 25 mm. This led to a different tyre profile being used in the simulation. This profile v2.33 was observed to be faster particularly in yaws of 5-15°.

This led to both profiles being taken forward to be tested in the tunnel to discern if this performance increase due to the wider tyre profile was due to any issues from the scanning process or if it was model-specific. The third profile tested was a version of the v2.19 where the nipple was internal, to see the magnitude of any drag reduction that may be achieved.

7.1 <u>Rear Profile Development</u>

The rear profiles were initially simulated as wheel-only models to look at the performance of the wheel in freestream airflow. The process 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 majority of the profile's performance.

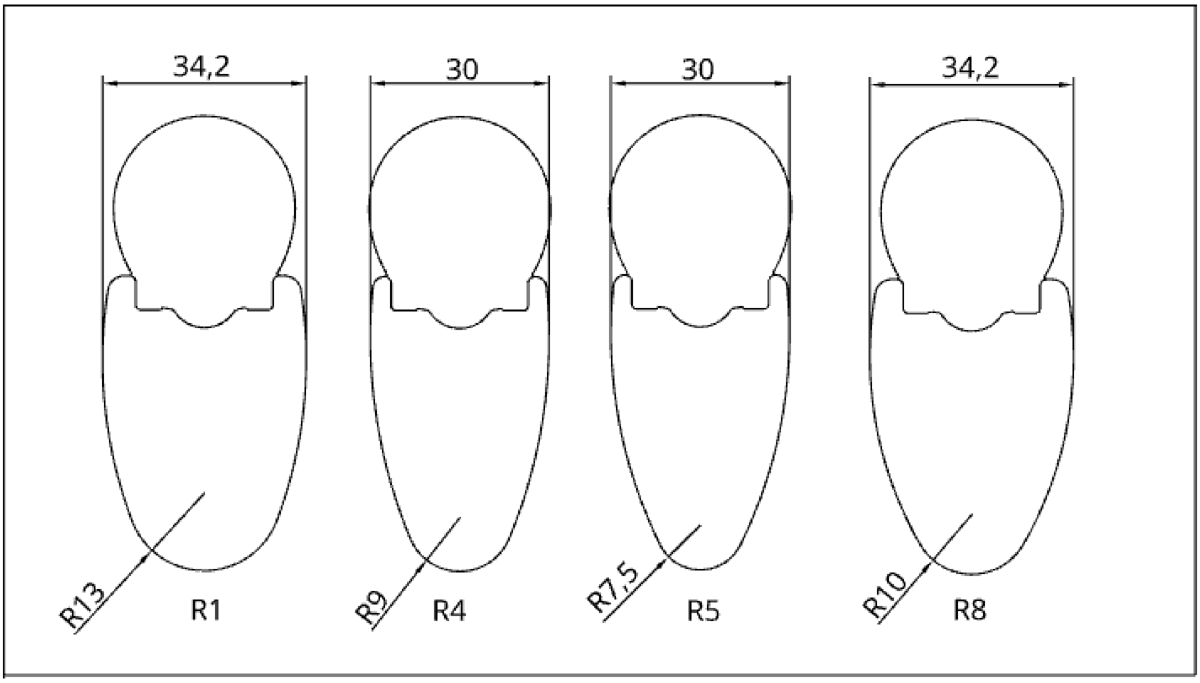

Figure 10 – Cross sections of early rear rim versions tested in full bike simulations.

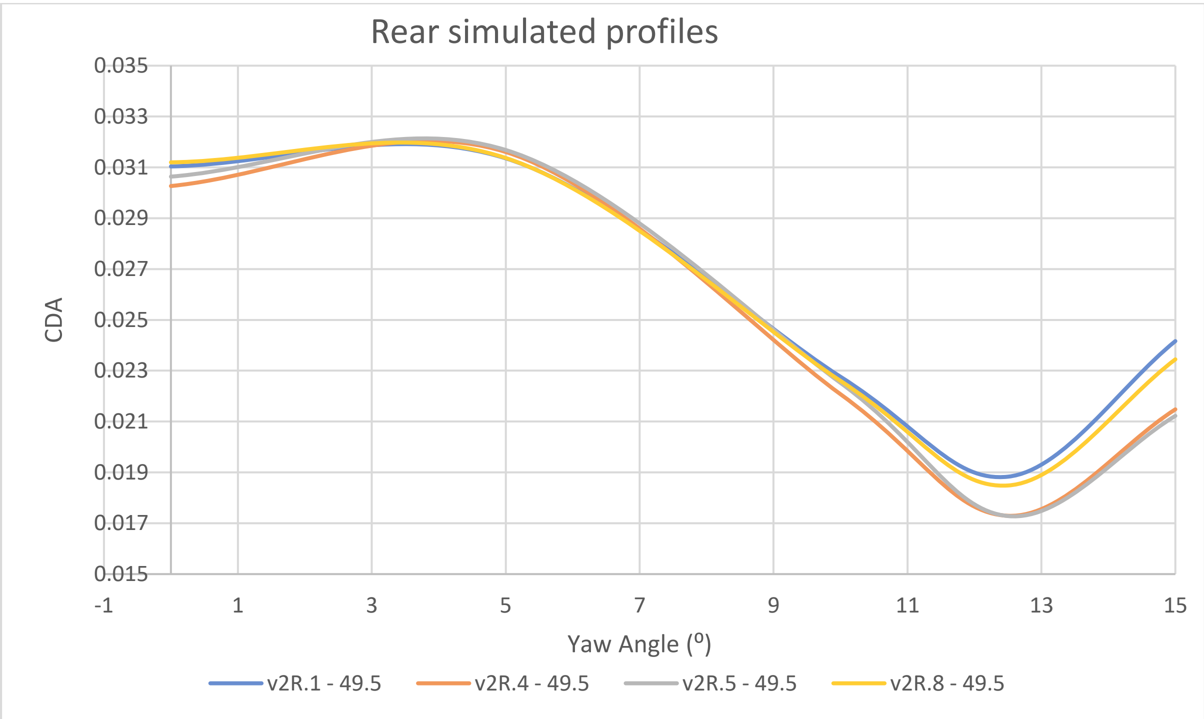

Figure 11 - Simulated full bike drag comparison 0° - 15°, demonstrating the effect of different rear profiles on CdA

The narrower profiles (v2R.4 and v2R.5) show an improvement in performance over the wider rear profiles (v2R.1 and v2R.8). With a small gain at the lower yaw angles with a smaller frontal area. Real separation is then seen at the higher yaws with the wider profiles causing more drag that the narrower profiles around the same width as the tyre.

7.2 Rim Depth

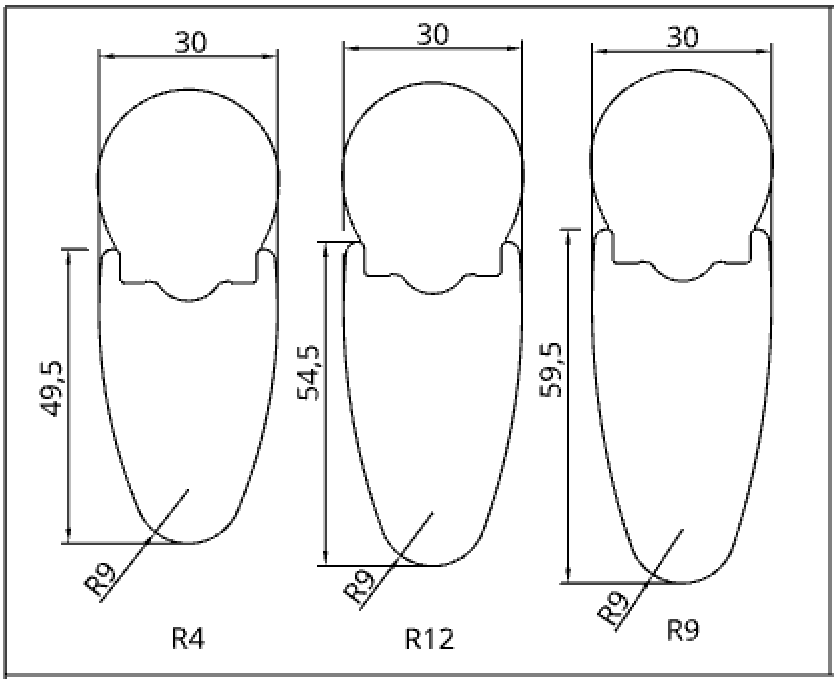

Figure 12 - Rear profiles with the same hook geometry at different depths

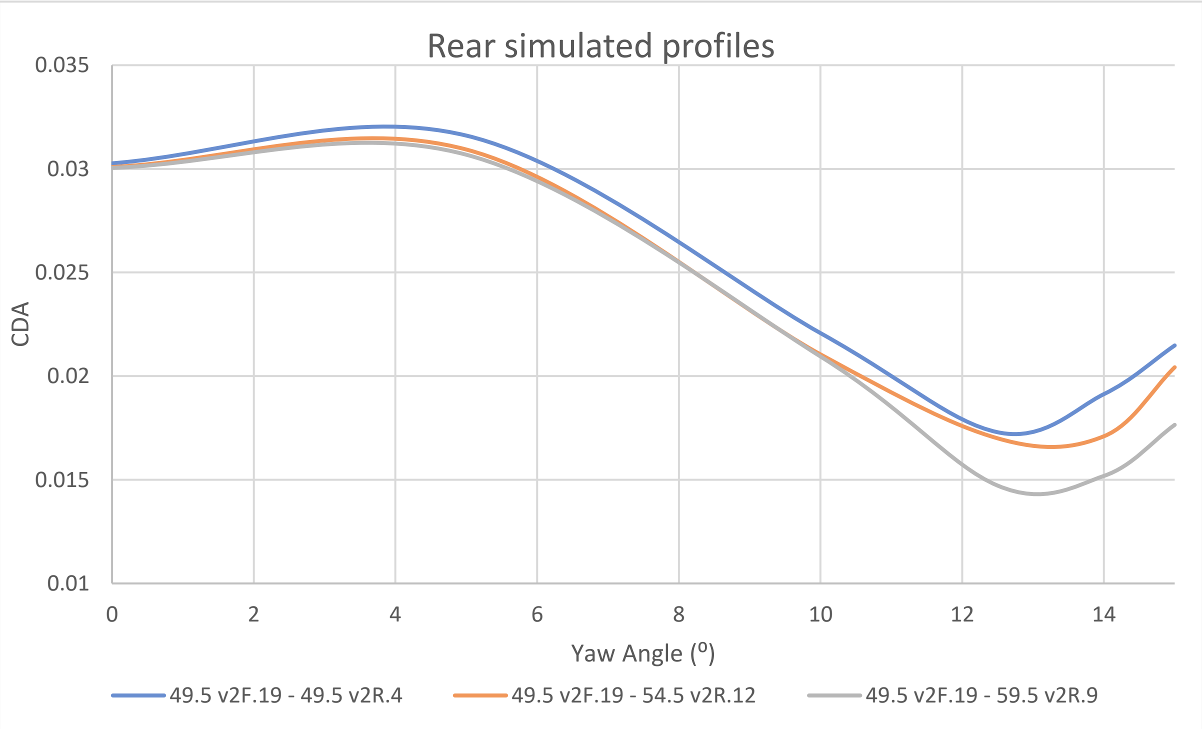

Figure 13 - Simulated full bike drag comparison 0° - 15°, demonstrating the effect of different rear wheel depths on CdA

Keeping the geometry, the same with just the depth changing, it can be seen that deeper rims create less drag. There were some small reductions in drag at lower yaw angles but the 59.5 mm deep profile shows real separation at higher yaw angles where the rim is providing the best sailing effect.

The profiles that were chosen to be taken forward were the vR.4 and vR.9, as well as a version of the v2.33 front profile laced for a rear hub and the 25mm internal of the v2R.4. The v2.33 was selected as the fastest profile tested in the freestream and is the closest profile to the current 48LAD which is known to test well in the wind tunnel. The 25mm internal width version was chosen so that the effects of changing the tyre shape could be evaluated.

7.0 Creation of wind tunnel Prototypes

For the first time all of the wind tunnel prototypes were produced in-house with the help and support of Formlabs.

The prototypes were printed in sections on an Stereolithography (SLA) printer creating a wheel that was strong enough to have a tyre mounted with little to no deformation but was also not prone to brittle fracture, as had been observed with 3rd party prototypes from previous tests.

Figure 14 - Wind tunnel prototype wheel.

The rims were printed in sections allowing for the patterns to be repeating. This minimised CAD set-up time and aided with assembly as all pieces were interchangeable, except one section with a valve hole. The rims were then built into wheels and trued and tensioned.

Figure 15 - Prototypes rims at the wind tunnel waiting to be tested.

4.3 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 authors returned to the GST Windkanal 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.

Figure 16 – Cannondale System 6 used for the 2023 wind tunnel testing.

3D printed prototype wind tunnel setup (August 2022):
Bike: Scott Foil 2022
Tyres: Schwalbe Pro One 28- and 30-mm TL
Tyre Pressures: 3D printed prototypes 30 psi for prototypes, 60 psi for all carbon wheels
Wind and Roller Speed: 45 kph
Yaw Angles: -20° to 20°.

Final production test setup (June 2023):
Bike: Cannondale System 6
Tyres: Schwalbe Pro One 28- and 30-mm TL
Tyre Pressures: 60 Psi
Wind and Roller Speed: 45 kph
Yaw Angles: -20° to 20°.

The wind tunnel is an important tool in HUNT's aerodynamic development. It permits changes to the tyre shape and size without having to analyse the model and adds in the realism of full bike and of different bikes very easily if that is desired. This is very 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 very small differences in drag to be picked up between runs, but the control of the environment does still forgo some realism

8.0 Steering Moment and Stability

As defined in the purpose of the wheelset, an important characteristic of any proposed front wheel design is to minimise steering force experienced in a cross wind and ensure stable handling across all yaw angles and conditions. The formula below explains how deeper section wheels are affected by side wind forces due to the greater area over which they act - Side Force (Fs) is directly correlated to Area (A):

$$F_s = \frac{1}{2}\rho\, V^2 C_s A$$

Equation 1 - Side force coefficient equation

Where:

F_S = Side Force

ρ = Air density.

V = Air speed

C_S = Side force coefficient.

A = reference cross sectional area.

Forces applied to the side of the wheel result in a response acting around the steering axis which are directly transferred to the handlebars. Drag and steering force characteristics are interlinked; whilst the airflow around the rim stays attached the magnitude of the steering moment grows until the airflow stalls. The nature of the response defines the predictability and stability of handling, where a non-linear response may create an unexpected handling feeling. The authors aimed to create a combination of two features to improve handling:

1. A linear variation in side force throughout as large a range of yaw angles as possible (primarily by delaying the stall point) – creating a more stable handling response.
2. Where possible, a lower overall side force which reduces the work the rider has to do in order to correct for a cross wind.

<u>Selection of competitor wheels</u>

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

- Wheelsets that are marketed for road disc brake use – ensuring a fair comparison with wheels designed for similar purposes and tyre sizes.

- Approximately 50 mm in depth – based on feedback from our supported riders 50mm was considered the best balance of drag, weight and cross wind stability for all-round road racing wheels.

- Internal rim width within +/-2.5 mm of the SUB50: The SUB50 has an internal rim width of 23 mm which lead to a 28 mm tyre to measure 28.5mm fitted on the rim. On wheels with a 20.5 mm internal width the tyre measures 27.6 mm. A 25 mm internal width the tyre measures 29.5 mm. A wider measured profile offers a host of benefits that are not observed in the wind tunnel: increased traction, comfort and reduce rolling resistance. As this paper is purely an analysis of the aerodynamic performance of these wheelsets to ensure a fair comparison, wheels with internal widths of 20mm or below were not included. There were no wheels from these manufactures with internal widths over 25mm that were approved for use with 28mm tyres.

9.0 Results

9.1 Front Prototype testing

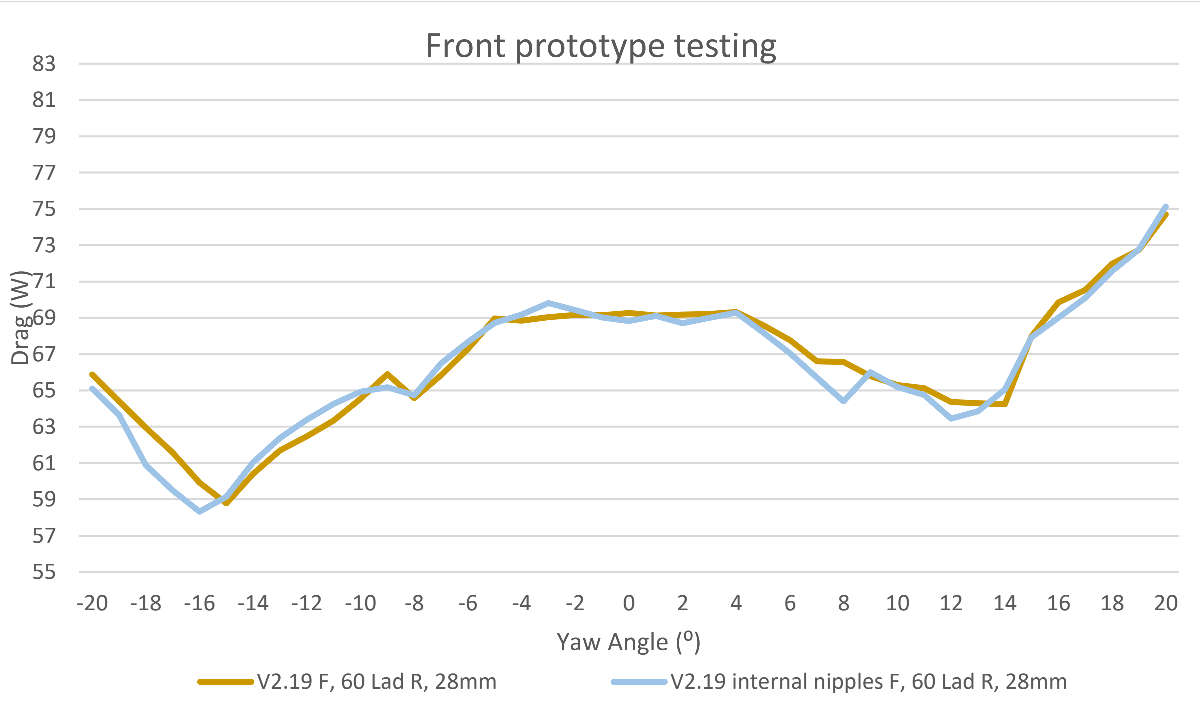

Figure 17 - Effect of internal nipples on the wheelset drag with the same profile v2.19.

The variance between the prototypes was very small with the internal nipple version of the rims showing a very slight drag reduction across nearly all of the range of yaw angles tested as would have been expected. After applying the WAD calculation, the drag saving was 0.2W, across both 28mm and 30mm tyres.

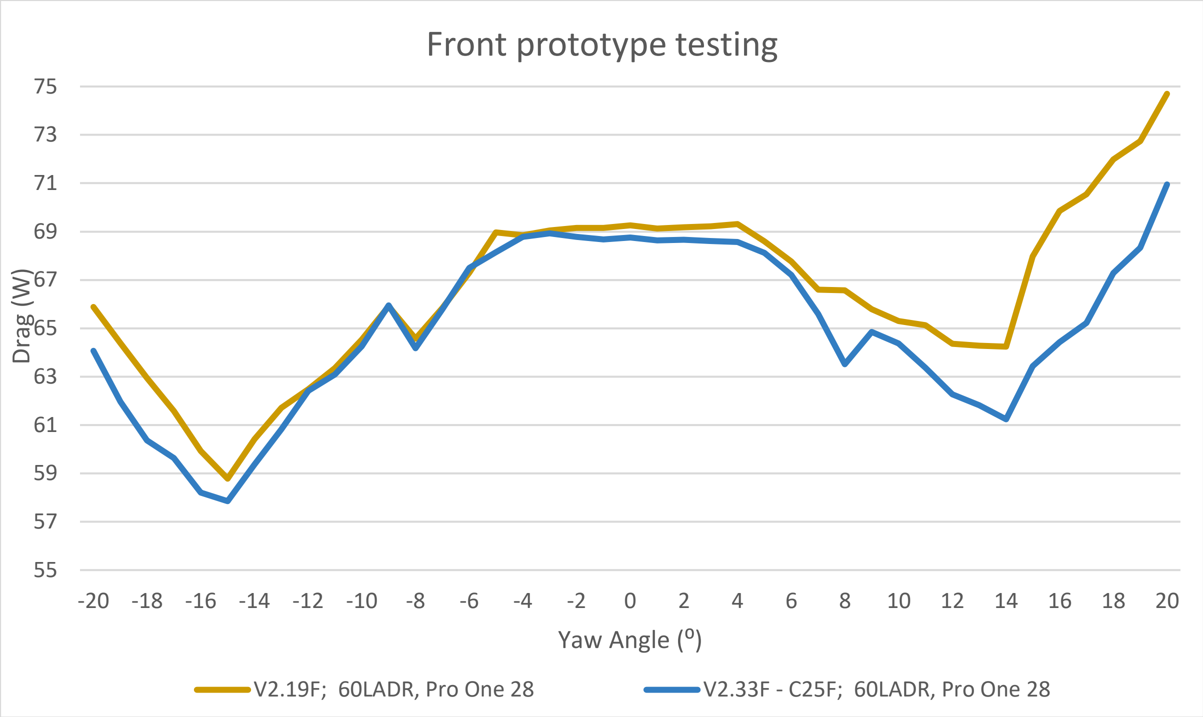

Figure 18 - Effect of internal rim width on drag with 28mm tyres (v2.19 = 23mm int, v2.33 = 25mm int)

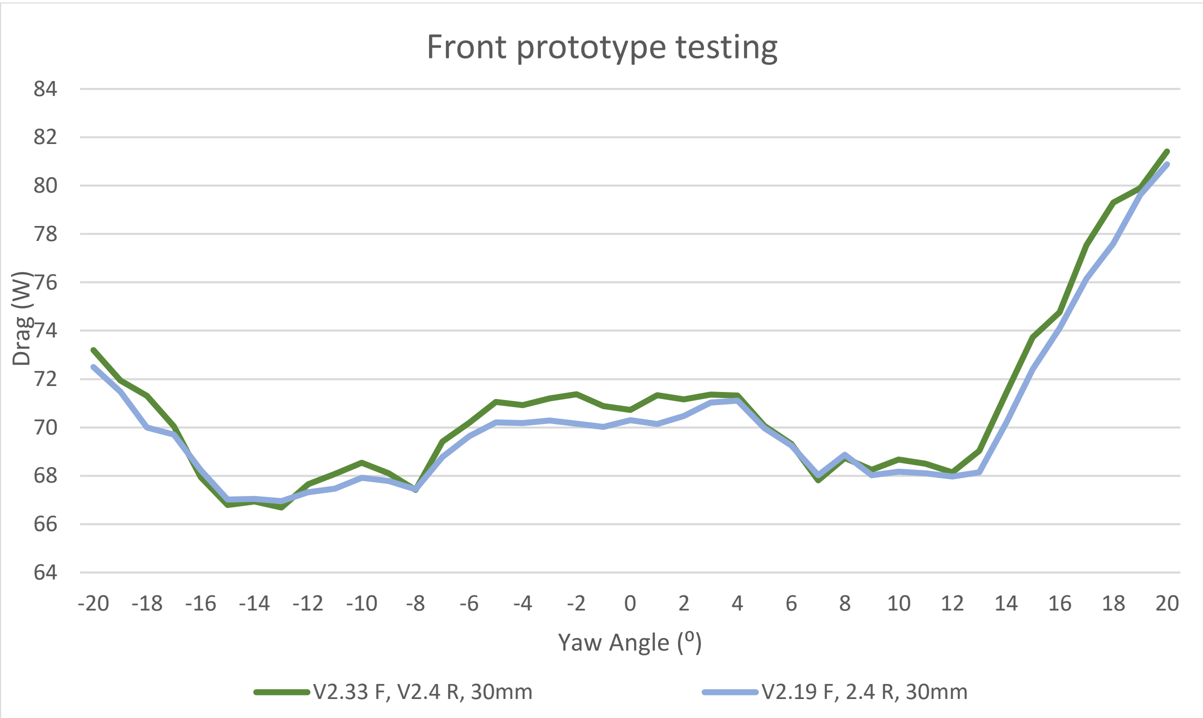

Figure 19 - Effect of internal rim width on drag with 30mm tyres (v2.19 = 23mm int, v2.33 = 25mm int)

Front wheel testing with 28 mm tyre				
Front wheel	Rear wheel	Tyre	Measured width (mm)	Power Mavic WAD (W)
v2.19 F - IntNpl	v2.4 R	Pro One 28	28.55	66.900
v2.33 F - C25	v2.4 R	Pro One 28	29.33	66.947
v2.19F	v2.4 R	Pro One 28	28.90	67.285
48LAD	v2.4 R	Pro One 28	28.43	67.729

Table 1 - Results of prototype testing with 28mm tyres.

Front wheel testing with 30 mm tyre				
Front wheel	Rear wheel	Tyre	Measured width (mm)	Power Mavic WAD (W)
v2.19F	v2.4 R	Pro One 30	30.65	69.096
v2.33 F - C25	v2.4 R	Pro One 30	28.58	69.102
v2.19 F – Int Npl	v2.4 R	Pro One 30	30.95	69.513

Table 2 - Results of prototype testing with 30mm tyre.

With these two profiles having identical external profiles; large differences are not expected but the differences show how powerful matching a tyre profile to the rim profile is. Good correlation to the simulation was observed with the 28mm tyre; the v2.33 shows separation from the v2.19 at higher yaw angles. This led to a lower averaged drag with the tyre sitting wider and squarer due to the changed tyre profile resulting in improved performance.

With the 30 mm tyre this relationship is flipped with the wider tyre on the 25 mm internal rim leading to larger drag at low yaw angles being observed due to the increase in frontal area of the tyre. The performances at higher yaw angles are then very similar with the 23 mm internal still being slightly ahead.

When averaged the results across both tyre sizes are well within the error of the wind tunnel. With the v2.33 being 0.29W faster with the 28 mm tyre and the V2.19 being 0.12W faster with the 30mm tyre. The v2.19 design was chosen for production samples following the release of new ETRTO guidance which states a 28 mm tyre should be fitted on rim wider than 23 mm internal.

10.0 Rear Prototype testing

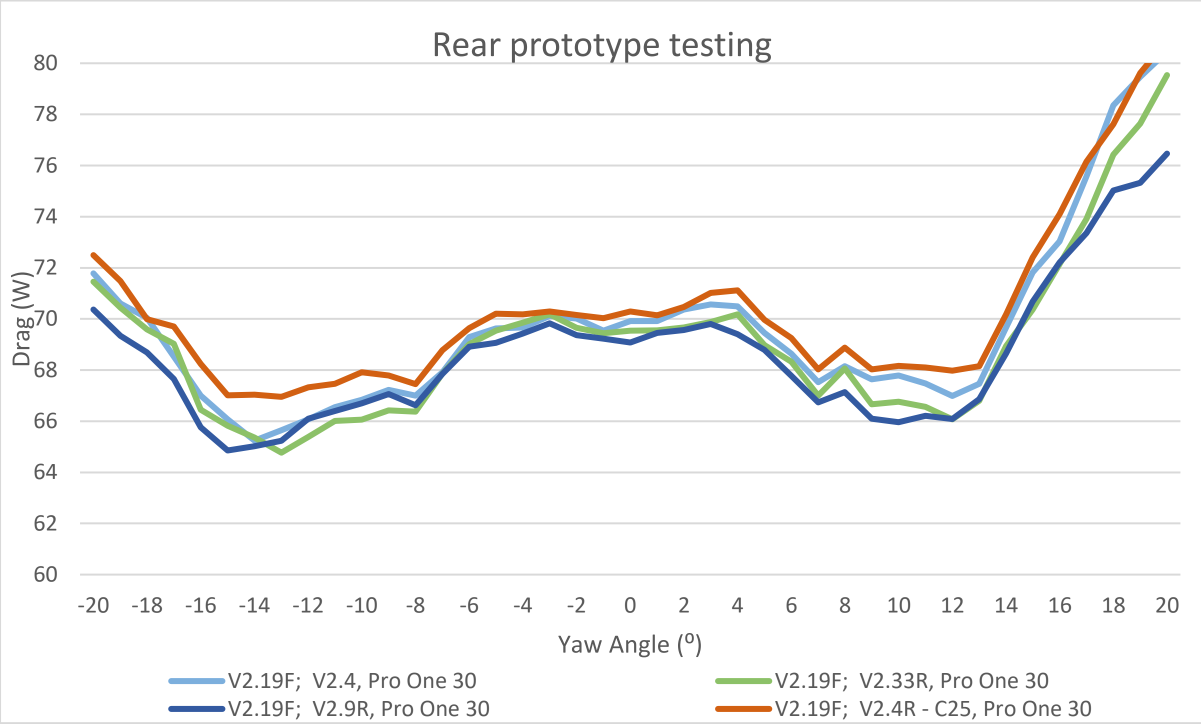

Figure 20 - Prototype testing, of all the wheels taken showing the drag from -20° to 20° with a 30mm tyre.

Rear wheel testing with 30 mm tyre				
Front wheel	Rear wheel	Tyre	Power Mavic WAD (W)	Power Mavic WAD (W)
v2.19F	v2.9 R	Pro One 30	30.50	68.30
v2.19F	v2.33 R	Pro One 30	31.53	68.57
v2.19F	v2.4 R	Pro One 30	31.15	69.10
v2.19F	v2.4 R - C25	Pro One 30	31.88	69.67

Table 3 - Results for rear prototypes with 30mm tyre

All of the profiles showed very similarly -shaped curves with the v2.33 being very impressive and showing low drag in yaw angles between 6° and 12°, even with the fact that the 30mm tyre is sitting very wide on its profile. The v2.4 R – C25 is the slowest of the set and the 0.7 mm wider tyre profile than the corresponding 23 mm internal model shows a 0.55 watt increase in drag. The v2.9R is a little disappointing here not showing the expected significant reduction in drag considering the 10mm increase in depth.

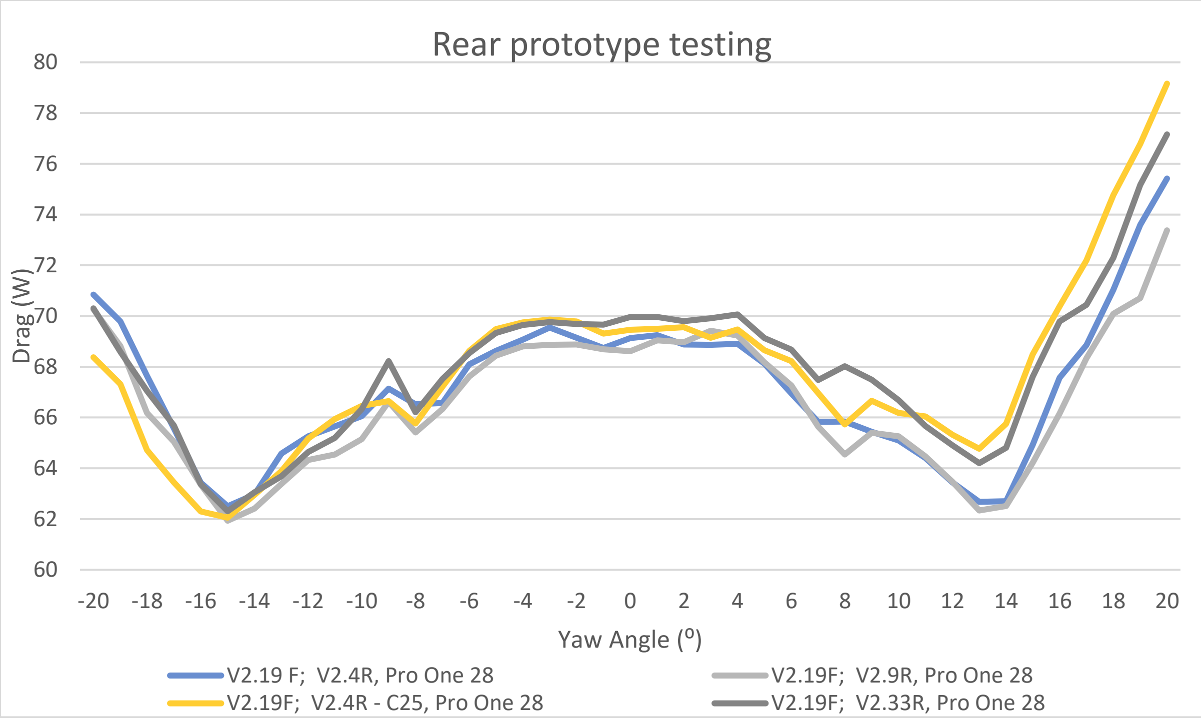

Figure 21 - Prototype testing, of all the wheels taken showing the drag from -20° to 20° with a 28mm tyre.

Rear wheel testing with 28 mm tyre				
Front wheel	Rear wheel	Tyre	Measured width (mm)	Power (W)
v2.19F	v2.9 R	Pro One 28	29.60	66.92
v2.19F	v2.4 R	Pro One 28	28.80	67.28
v2.19F	v2.4 R - C25	Pro One 28	29.16	68.04
v2.19F	v2.33 R	Pro One 28	30.13	68.17

Table 4 - Results for rear prototypes with 28mm tyre

Apart from the v2.9R design, the 28 mm testing shows a different ranking of the samples to the 30mm, with v2.4R being well ahead of similar depth designs with considerably better performance at higher yaw angles and a little ahead across most of the rest of the range of yaw angles. Both the 25mm internal designs exhibited similar performances and were observed to have extra drag at both low yaw angles and then with larger separation at higher yaw angles.

The v2.4 profile was chosen for the production samples, as it offered the best performance with both the 28 and 30mm tyres and it would match the tyre compatibility of the front profile, while also being a narrower external width with excellent aerodynamic performance when used as a rear wheel – helping achieve the overall purpose of the wheelset.

11.0 Selection of final rim designs

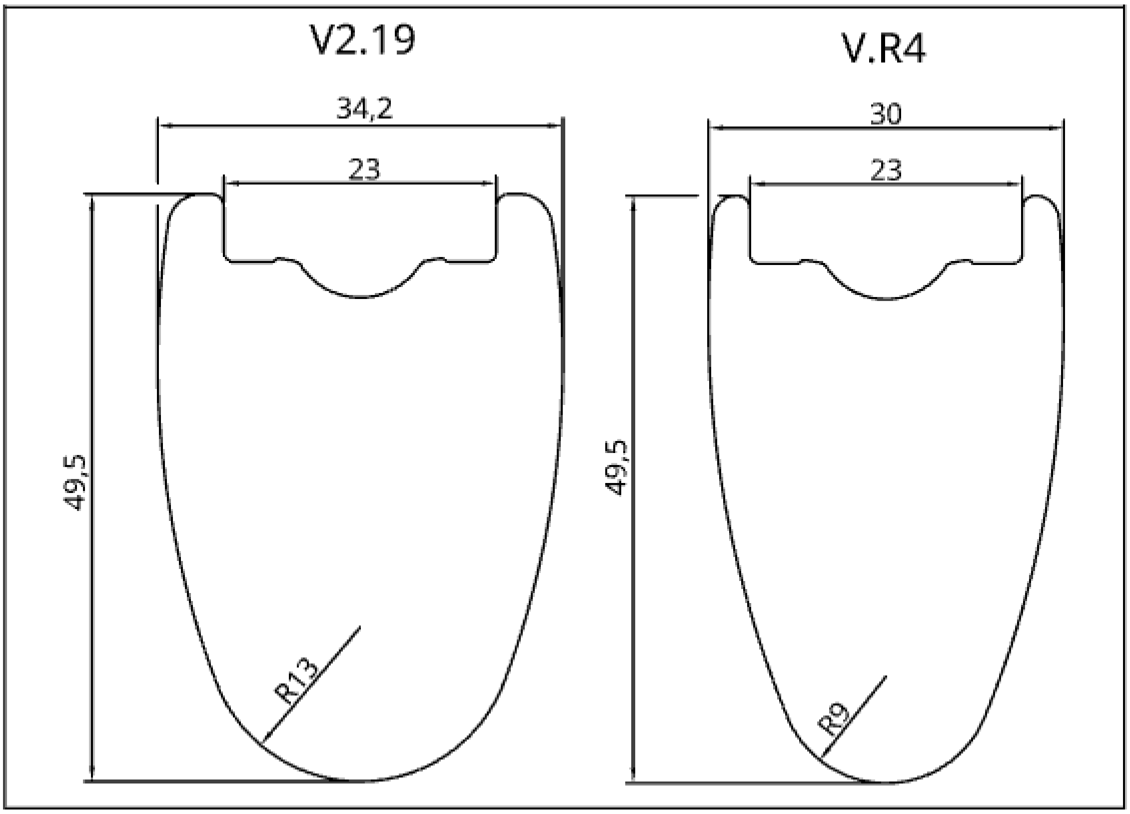

Figure 22 – Cross section of finalised profiles for carbon prototype testing

The v2.19 and vR4 designs were selected as the final combination to create a production sample wheelset that could be tested against the leading competitors with the intention to be the best all round road racing wheelset available.

The front design (v2.19) was chosen since with 30mm tyres it outperformed the V2.33 while being very similar in performance with a 28mm tyre and the internal width allows compatibility with both tyre sizes in the latest ETRTO guidance. The vR4 rear profile was the fastest 49.5 mm deep profile that we tested, showing very good aerodynamic performance for its depth and therefore using less material and helping to reduce the overall weight of the wheelset. It was decided that these profiles would offer the best combination of aero performance, aero stability, weight and tyre compatibility.

12.0 Finished carbon fibre prototype wind tunnel results.

This wind tunnel trip was carried out at the height of the Summer in southern Germany which lead to a temperature swing of 22°C during the day. This quite dramatically changed the Reynolds number of the flow in the tunnel. This change would be equivalent to changing the wind speed from 12.5 m/s to 13.2 m/s. As the runs are controlled for wind speed rather than Reynolds number wheels tested close to each other are going to be the only ones that will be directly comparable to one another. The tests referenced here are exclusively be taken from the morning session where the temperature was most consistent. The full list of results can be found in the appendix.

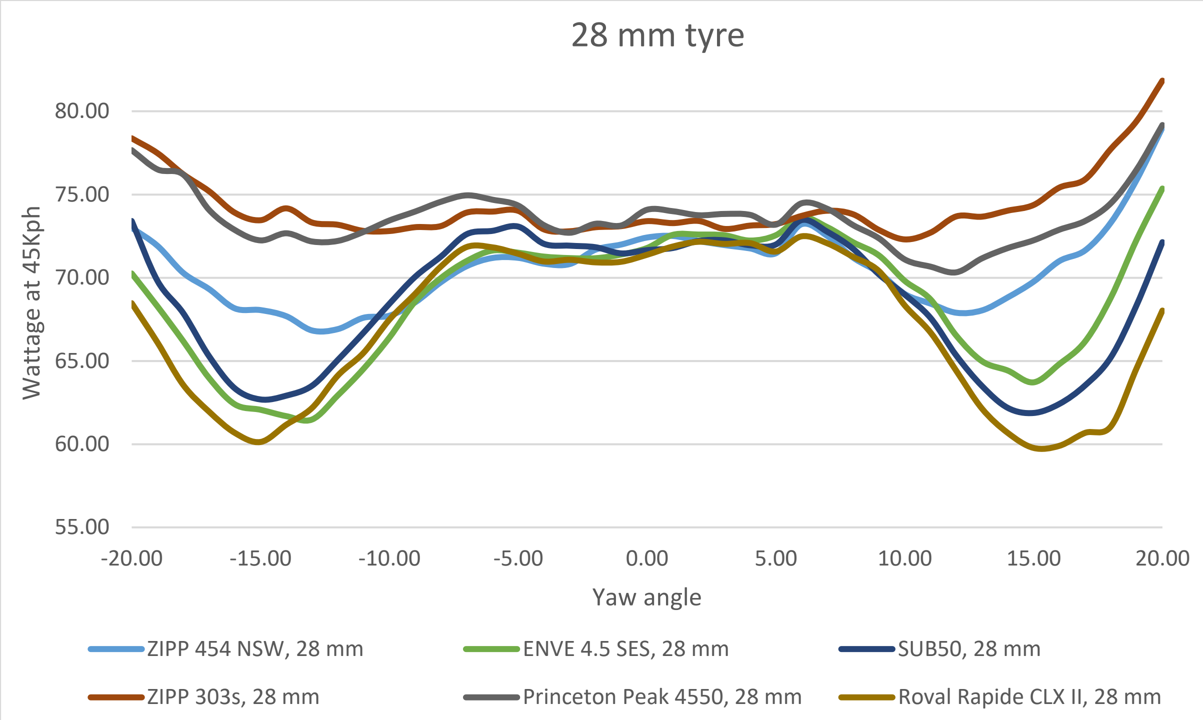

Figure 23 - Results for the key competitor set through -20° to 20°, with a 28mm tyre.

At low yaw angles we can see that generally those wheels with deeper and narrower profiles exhibit the lowest drag figures. At around 7°-8° the wider profiles start to reduce in drag as they start to generate a sailing effect. This is where the SUB50, Roval Rapide and Enve 4.5 SES separate themselves from the competition showing a much greater ability to keep the flows attached and hold off stall until much higher yaw angles.

The Enve has a very asymmetrical drag profile in this graph with very good performance in negative yaw angles and less strong in positive yaw angles and it is hard to say what causes this without further study. It is likely to be an interaction between the frame, drive train and discs with the specific geometry of the rim to increase or decrease performance in one configuration.

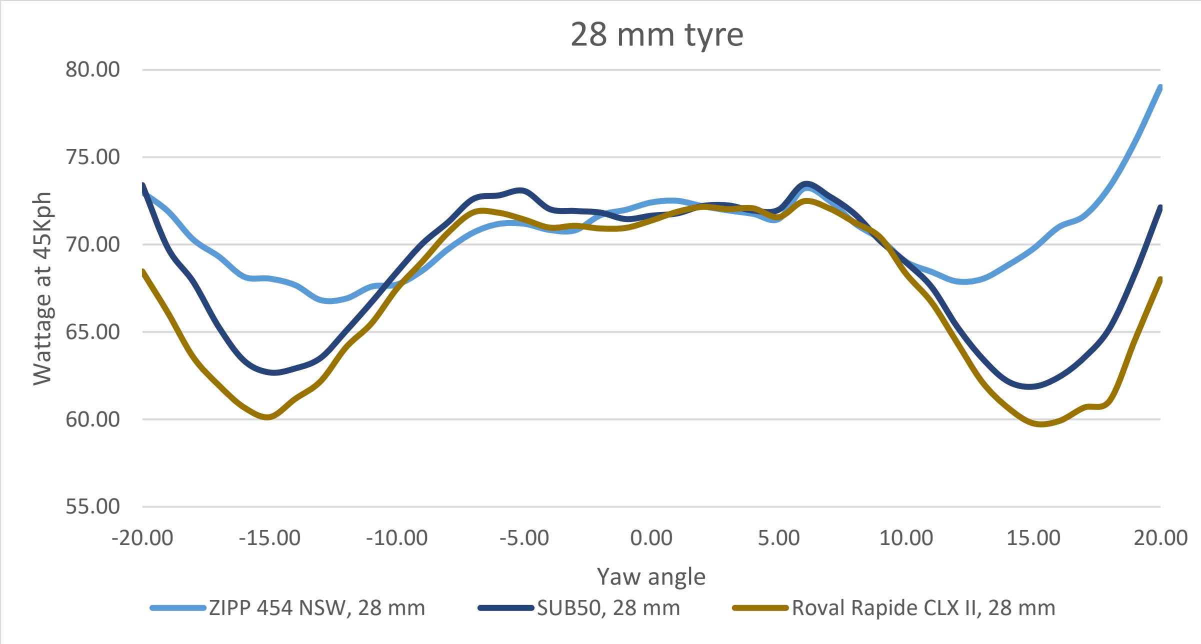

Figure 24 - Results for the fastest wheels through -20° to 20°, with a 28mm tyre.

Looking at the faster profiles the Roval Rapide is the most efficient profile on test with low drag across the full range of yaw angles with the latest stalling point. This is achieved with a combination of the wider front profile and the relatively narrow 21mm internal rim width, creating a very effective tyre-rim combination albeit with the lowest measured tyre width of the wheels tested.

The Zipp 454 shows low drag at low yaw angles with the narrower form reducing its frontal area. However, it does not provide the sailing effect that the wider SUB50 and Roval exhibit. This leads to it having a higher overall drag figure than the SUB50 in this test.

28 mm WAD data					
Wheelset	Power Mavic WAD (W)	Nominal tyre size (mm)	Measured width - F & R Averaged (mm)	Averaged depth (mm)	Claimed weight (g)
Roval Rapide	69.22	28	28.09	56.0	1520
ENVE 4.5 SES	69.97	28	29.79	53.5	1511
SUB50 UD	70.12	28	28.23	49.5	1378
ZIPP 454 NSW	70.81	28	28.60	58.0	1428
Princeton Peak	73.48	28	27.58	50.0	1488
Zipp 303 s	73.70	28	28.28	45.0	1540

Table 5 - Results with a 28mm tyre

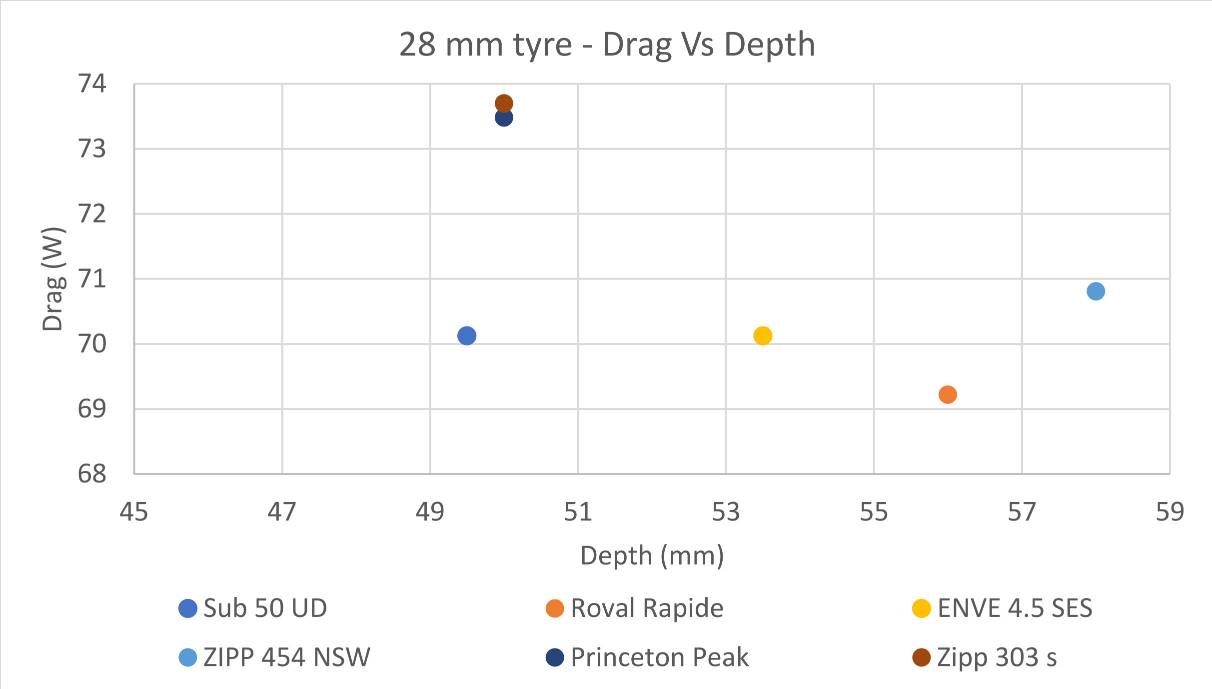

Figure 25 - Drag compared to wheelset depth, with a 28mm tyre.

Of wheelsets of a similar depth the SUB50 stands out clearly from the rest of the sample having a much more efficient profile for the depth of rim, and with drag numbers close to or exceeding the deeper wheels in the test.

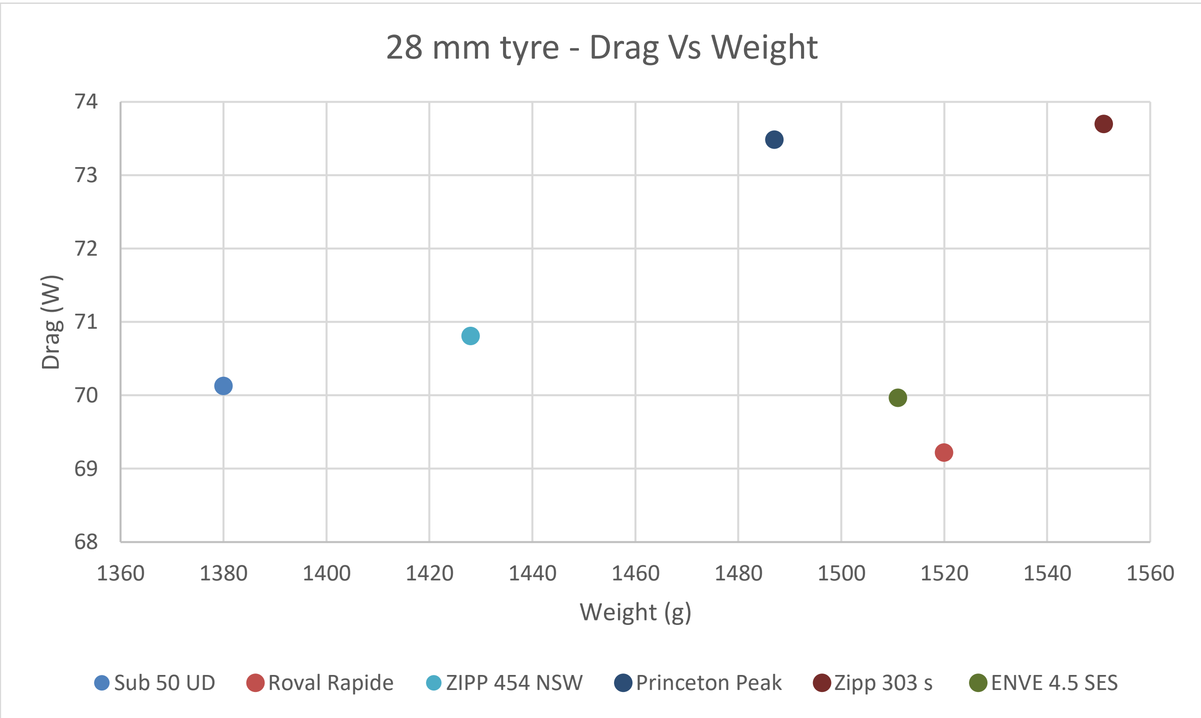

Figure 26 - Drag compared to wheelset claimed weight, with a 28mm tyre.

With a 28 mm tyre the SUB50 UD and the Zipp 454 NSW have the lowest drag compared to the wheelset's weight. This provides versatility: pure aerodynamic performance among the very best tested while also being some of the lightest all-round wheels available.

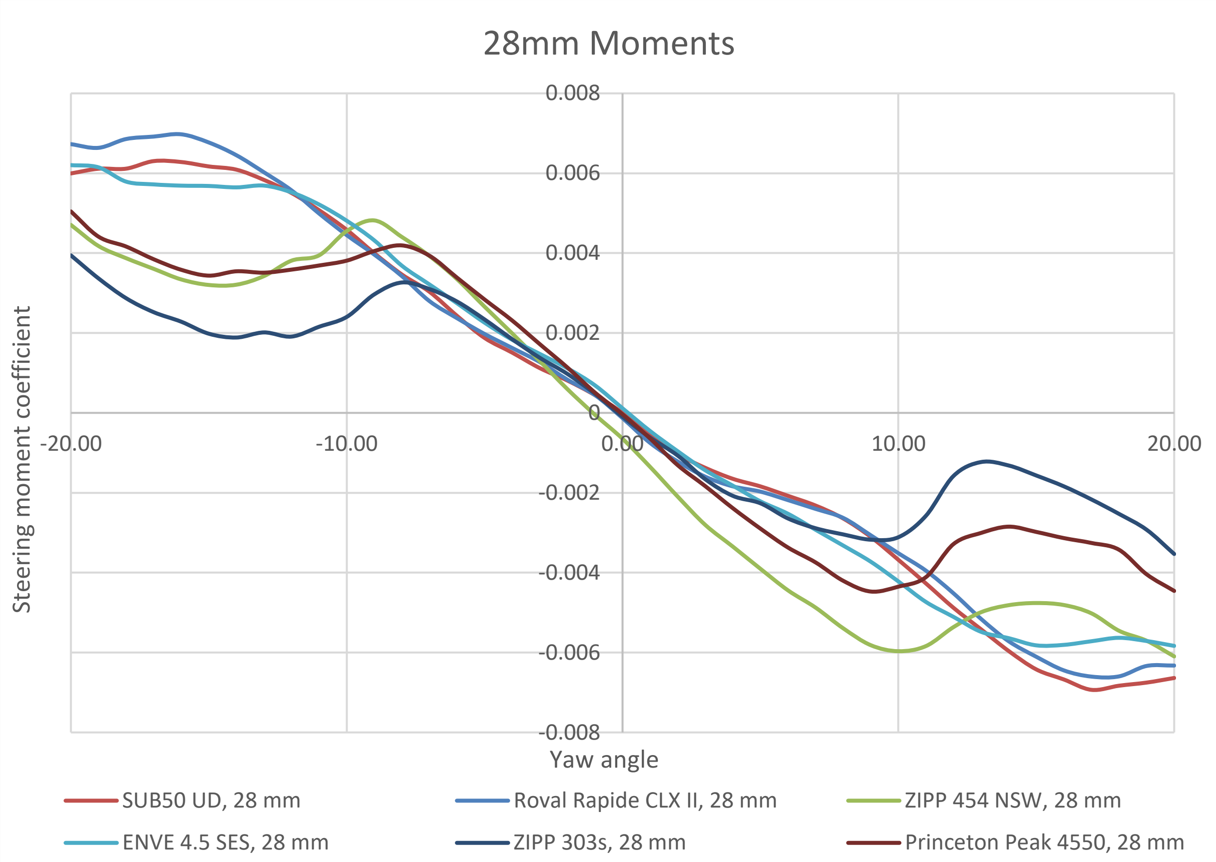

Figure 27 - Graph showing the steering moment coefficient with a 28mm tyre through -20° to 20°.

The narrower rim profiles of the Zipp 303s, Princeton, and Zipp 454 NSW have higher side forces at low yaw angles up to around 10° by which time all three wheelsets experience stall. At this point there is a rapid reduction in steering moment.

The Sub-50, Rapid and Enve wheelsets share a similar behaviour to each other with lower steering moments up to around 10° yaw, but they do not experience stall until around 16°. This later stall achieves lower average drag and a more predictable change in steering moment as the wind conditions change – albeit with a higher overall steering moment at the highest yaw angles.

It is difficult to precisely translate this behaviour to real world riding experiences, but as a rule the narrower designs may experience more unpredictable handling in changing wind conditions. The wider wheels are likely to be more predictable, albeit with the need to apply a higher overall correcting force at the handlebars in very high yaw angle conditions.

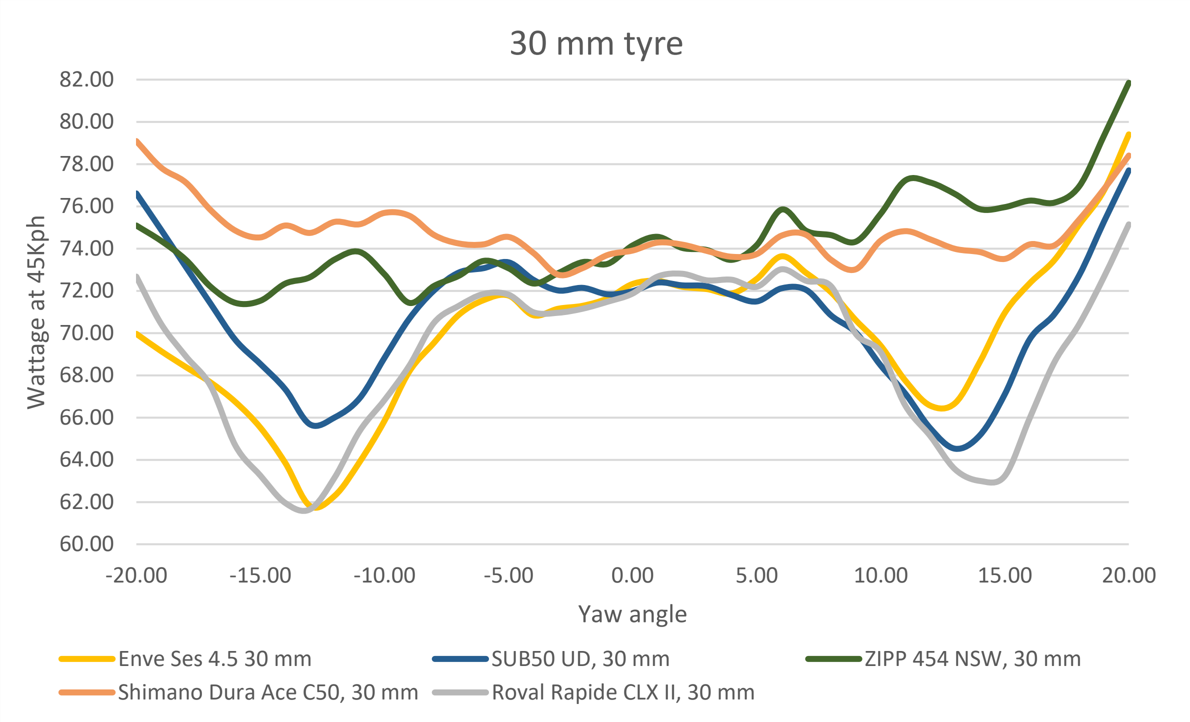

Figure 28 - Results for the key competitor set through -20° to 20°, with a 30mm tyre.

The Zipp 454 and Dura Ace C50 are both 28 mm wide externally, and this clearly has a negative effect on their aerodynamics with a 30mm wide tyre. There is no notable sailing effect at any yaw angle, and this is in line with what is expected when the tyre is wider than the rim, where flow separation will occur very early and lead to a large increase in drag. (The C50 was tested with a 28mm tyre and it saw an improvement in performance but this was in the afternoon set, making it not a fair comparison to the other 28mm results analysed.)

The rest of the wheels all have a similar shape to their drag curves with stall occurring at 13°-15°. This is possible as all these rims are 32 mm or wider allowing more efficient airflow over the rim. The Enve again shows a very asymmetric drag curve but is a stand-out on this test being only 0.4W behind the Roval and having a tyre profile measuring 1.2mm or 4% wider. Again, the Roval wheels have the narrowest measured tyre width of the wheels tested.

30 mm WAD data					
Wheelset	Power Mavic WAD (W)	Nominal tyre size (mm)	Measured width - F & R Averaged (mm)	Averaged depth (mm)	Claimed weight (g)
Roval Rapide	70.07	30	30.20	56.0	1520
ENVE 4.5 SES	70.52	30	31.44	53.5	1511
SUB50 UD	71.04	30	30.90	49.5	1378
ZIPP 454 NSW	74.11	30	30.91	58.0	1328
Dura Ace C50	74.40	30	30.64	50.0	1465

Table 6 - Result with a 30mm tyre.

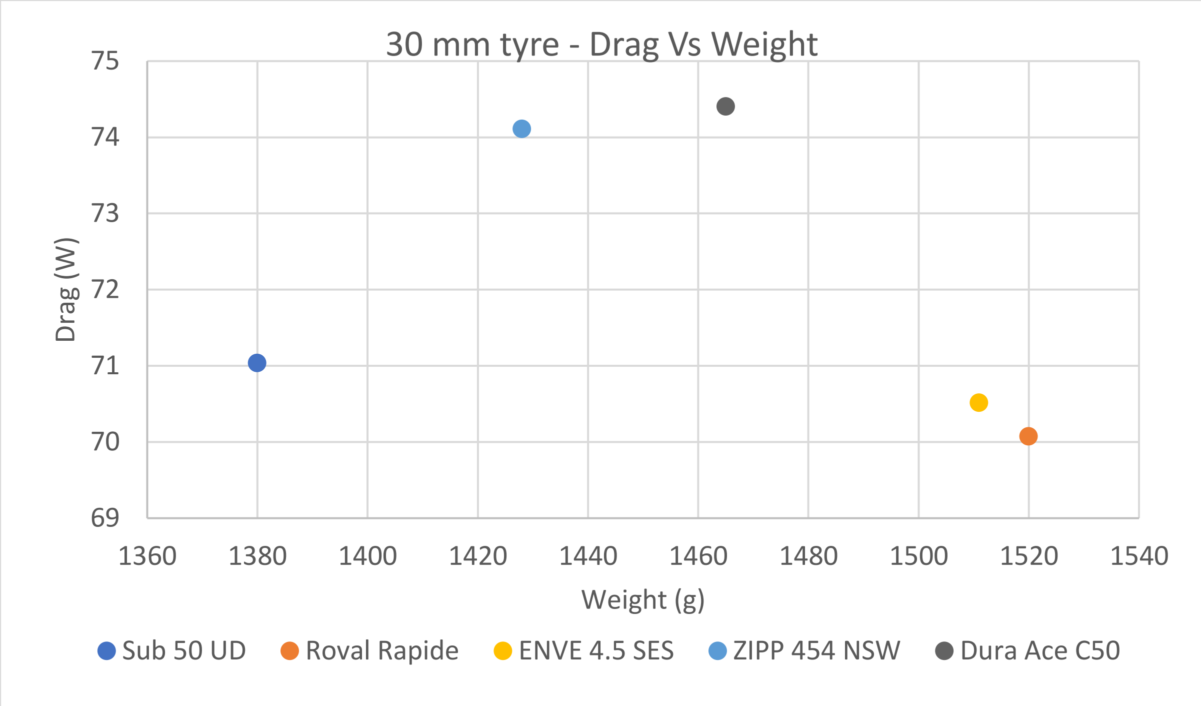

Figure 29 - Drag compared to wheelset claimed weight, with a 30mm tyre

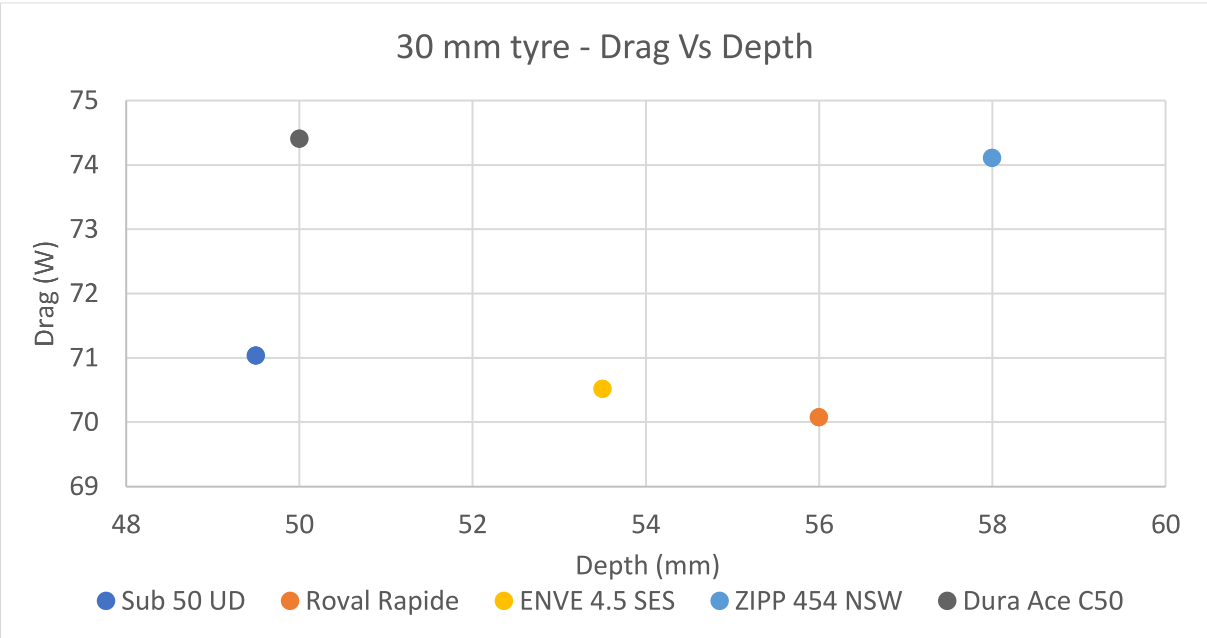

Figure 30 - Drag compared to wheelset depth, with a 30mm tyre.

As with the 28mm tyre results, these graphs show that the SUB50 is using its material efficiently to provide a wheelset that performs very well for its weight and depth.

The Enve and Roval wheels achieve slightly lower drag figures with higher rim depths and weights.

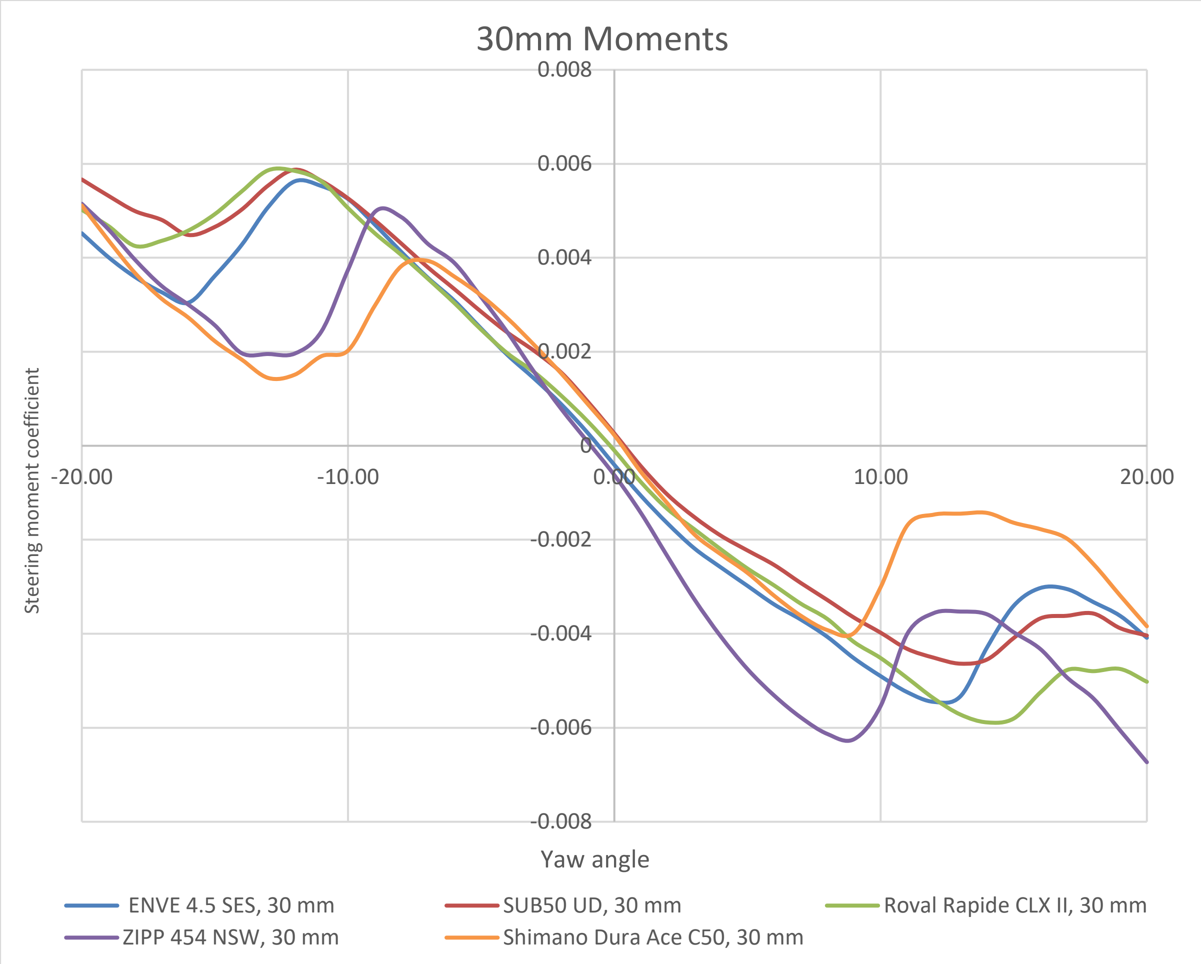

Figure 31 - Graph showing the steering moment coefficient with a 30mm tyre through -20° to 20°. The steering moment behaviour changes slightly with a 30mm tyre, with the wider external width wheels all showing an earlier stall as the wider tyre makes it harder to prevent flow separation.

The SUB50 shows the smoothest behaviour through the stall point which should ensure predictable handling at all yaw angles as discussed above for the 28mm tyre.

13.0 Conclusions

The aim of this project was to create a new wheelset building on the technological groundwork of the 48LAD wheelset and other aerodynamic development projects carried out by the HUNT team to create a new wheelset – with the purpose of being the best choice for an all-round road racing wheelset available.

Compared to the 48LAD the SUB50 reduced drag by 1.4W with a 28mm tyre and reduced overall wheelset mass by over 130g to 1378g for the carbon spoke version. In comparison to the leading competitors in the test:

- With a 28mm tyre the SUB50 had third lowest aerodynamic drag after the Enve 4.5 SES (0.15W difference) and Roval Rapide (0.9W difference). The SUB50 had a lower drag than the Zipp 454NSW, Princeton Peak and Zipp 303s (0.69W, 3.36W, and 3.58W difference respectively).

- With a 30mm tyre the SUB50 had third lowest aerodynamic drag after the Enve 4.5 SES (0.52W difference) and Roval Rapide (0.97W difference). The SUB50 had a lower drag than the Zipp 454NSW and Shimano Dura-Ace C50 (3.07W, 3.36W difference respectively).

- Compared to the manufactures claimed weights of the Enve and Roval wheels the SUB50 saves riders 131g and 140g respectively and lower depths. The 23mm internal rim width of the SUB50 provides a wider measured width for a given tyre, compared to the Roval wheels, while maintaining compatibility with both 28mm and 30mm tyres according to the ETRTO guidance.

Other testing was carried out, with full results in the appendix. The DT Swiss Dicut performed best of these wheels (but the 20mm internal width fell outside the limits defined for the competitor set). The DT Swiss wheels showed and average 0.37 W saving with a 28mm tyre, while the SUB50 saved 1.85W with a 30mm tyre. However, the narrower internal rim width resulted in a measured width almost 1mm narrower with the DT Swiss rim.

The steering moment data and rider testing show that the wheels provide the confidence needed for racers to hold low drag positions with confidence for longer whatever the wind conditions, improving their racing speed.

The wider internal rim width allows riders to take advantage of the rolling resistance benefits that come with wider tyres, on all road conditions but especially on rougher racing surfaces and cobbles.

Upon reviewing the drag data, production mass, depth profile and handling characteristics the HUNT team concluded that the SUB50 met the purpose of the wheels, and the wheelset was taken forward into production. It is an all-round racing wheelset with the drag characteristics amongst the very best wheels available and a low weight and wide measured tyre profile characteristics that make it excellent for any racing condition including mountains, cobbles and cross winds.

14.0 Evaluation and Further work

The comparisons of CFD and wind tunnel data show an improvement in correlation and give confidence both in the conclusions drawn here and the continued use of these methods by the HUNT team in future. Despite the requirement for simplifications used in the CFD model the correlation with wind tunnel testing shows that this was an appropriate approach to make the most efficient use of development time and computing resources.

Weather conditions did change during the test and this does limit the ability to correctly compare different runs, and the authors avoided directly comparing runs carried out between the morning and afternoon sets. This experience will help future testing, as repeat runs can be performed as conditions change to ensure comparable data is captured without running out of wind tunnel time.

The HUNT team also wish to continue to pursue real world testing – at the time of writing this has not been possible and current evaluations of this approach show that it is difficult to achieve error margins small enough to allow a distinction between the best performing wheelsets. Similarly, the team are exploring options to represent the effect of turbulence on the aerodynamic performance. Again, this has a larger error margin and requires longer wind tunnel run times in order to average measured data. It is also not yet well understood how artificial turbulence created in a wind tunnel compares to measured turbulence experienced by a rider on the road.

15.0 Acknowledgements

Thank you to Ernst Pfeiffer at GST for all 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 used in all our rim development to date.

Thank you to all the staff at The Rider Firm, every one of whom have assisted this process, especially those who contributed to the early technical development of this project.

We would also like to thank Luisa Grappone and Chris Colenso, valued colleagues who built much of the groundwork of knowledge in CFD and wind tunnel testing in our team.

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 projects like these would not be possible.

References

[1] This is how wider tires and rims can make you faster | EF Education-EasyPost (efprocycling.com)

[2] Why Are Tires and Wheels Getting Wider? – Triathlete

[3] https://www.bicyclerollingresistance.com/specials/top-3-fastest-tubeless-vs-tubes

[4] Wider tyres go faster? - Continental Bicycle Tyres UK (conti-tyres.co.uk)

[5] https://www.huntbikewheels.com/blogs/news/cfd-an-explainer

Appendices

Complete list of competitor wheels, all tested in the Cannondale System 6 described above in the 2023 test and results in chronological order.

	Wheelset and tyre size	Power: Mavic WAD (W)	Fitted width F&R average (mm)
Morning set			
	SUB50 UD, 28 mm	70.12	28.23
	ENVE 4.5 SES, 30 mm	70.52	31.44
	Roval Rapide CLX II, 28 mm	69.22	28.09
	SUB50 UD, 30 mm	71.04	30.63
	ZIPP 454 NSW, 28 mm	70.81	28.6
	Roval Rapide CLX II, 30 mm	70.07	30.21
	DT Swiss Dicut 50, 28 mm	69.52	27.41
	ZIPP 454 NSW, 30 mm	74.11	30.91
	ENVE 4.5 SES, 28 mm	69.97	29.79
	DT Swiss Dicut 50, 30 mm	72.88	29.89
	SUB50, 28 mm	70.24	28.56
	48LAD STEEL SPOKE, 28 mm	71.53	28.35
	Mavic Cosmic SLR 45, 28 mm	72.54	27.2
	ZIPP 303s, 28 mm	73.70	28.28
	Princeton Peak 4550, 28 mm	73.48	27.58
	34 AWD, 28 mm	76.70	27.61
	ENVE 4.5 SES, 30 mm, repeat	70.27	31.83
	4SEASON DISC, 28 mm	81.76	27.24
	50CAD, 28 mm	74.02	28.58
	54AD, 28 mm	71.82	27.74
	Shimano Dura Ace C50, 30 mm	74.40	30.64
Afternoon set			
	ZIPP 353, 30 mm	76.25	32.02
	Roval Rapide CLX II, 28 mm, repeat	69.84	28.21

	SUB50 UD, 30 mm, repeat	72.20	30.9
	ZIPP 454 NSW, 28 mm, repeat	72.58	30.61
	Roval Rapide CLX II, 30 mm, repeat	71.20	30.61
	DT Swiss Dicut 50, 28 mm, repeat	71.37	27.6
	ZIPP 454 NSW, 30 mm, repeat	75.25	31.54
	ZIPP 353 NSW, 28 mm	73.54	29.46
	DT Swiss Dicut 50, 30 mm, repeat	73.33	29.86
	Shimano Dura Ace C50, 28 mm	71.84	28.23