The HUNT 40 Limitless Gravel Aero

Designing and testing the ideal wheelset for long distance one-day gravel races.

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1.0 Introduction

HUNT Bike Wheels was founded in 2015 with the launch of the 4 Season Disc wheel, which while aimed at road riders soon gained a reputation for toughness and began to be used on gravel tracks. Just one year later HUNT saw the potential growth of the gravel market and introduced their first gravel wheelset: the 4 Season Gravel Disc which remains part of the HUNT range to this day.

In 2021 HUNT developed the 42 Limitless Gravel Aero (42 LGA) wheelset aerodynamically developed for the worlds' biggest one-day gravel races such as Unbound. HUNT's wind tunnel testing showed the 42 LGA to be faster than the wheels on offer at that time from both Zipp 303 NSW and ENVE 3.4 AR. It has been used since then by HUNT sponsored athletes with success in numerous gravel races such as 5th at Unbound Gravel in 2023.

As gravel racing develops, a wider variety of courses have emerged, driving a requirement for both excellent aerodynamic performance but also lower mass.

The HUNT design team recognised that some of the technology used in the newly developed SUB50 road racing wheels could be utilised to develop a new wheelset that builds on the class-leasing aerodynamic performance of the 42 LGA and significantly reduced mass.

The 40 Limitless Gravel Aero (40 LGA) was designed to be the fastest all-round gravel racing wheelset available, combining leading aerodynamic performance, low mass and crosswind stability. In order to achieve this the team established a design brief for the project:

- A mid-depth wheelset specifically designed for mass-start gravel racing use.
- Maintain the aero efficiency benefits achieved by the category-leading HUNT 42 LGA wheels, while significantly reducing system weight and optimizing rim shapes around wider modern gravel tyres.
- Optimise front and rear rim profile shapes to maximize aerodynamic performance for the specific wind conditions at the front and rear of the bike.
- Optimise rim profiles for the best aerodynamic performance with wider 40mm and 45mm 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.
- Design tyre bed in compliance with the latest ETRTO tubeless standards for the applicable tyre sizes.

The rims were optimised to work with 40-45 mm gravel tyres. Wider, more ‘knobbly’ tyres were not used in the development process as the turbulence generated by the side knobs becomes the dominant factor in determining the drag of the tyre/wheel system.

3D printed prototypes were used to validate the Computational Fluid Dynamics (CFD)- derived profiles. Once production rim samples were available, these were then wind tunnel tested against the current HUNT 42 LGA and a range of competitor wheels. There follows a brief description of the process used for this development project, together with detailed results of the testing carried out.

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.

The wheels were then tested in prototype form in the 2024 Unbound Gravel Race with excellent results including a 10th place for Sarah Lange in the Elite Women 200 category.

2.0 HUNT 40 LGA Front profile

2.1 Initial CFD Development

In the initial development stages, no parameters were fixed, with the objectives of creating a very aerodynamically efficient profile whilst maintaining high levels of aerodynamic stability. The project took account of the feedback from our professional riders, that a reduction in the wheelset weight and a broader hook for pinch flat protection would be desirable.

The depths were selected to be 40mm deep for the front and 41mm for the rear. 40mm is a sweet spot for gravel race wheels, as with a large tyre, deep section wheels can present a large cross-sectional area to wind gusts. Some depth was added to the rear rim to increase the aero performance and stiffness of this profile.

The initial tests on the front wheel were run as wheel-only simulations 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. The tyre used for this test was a 40mm Schwalbe G-One Allround, which was scanned on 27- and 26-mm internal rims 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 profiles were tested from 0° to 15° yaw angle as this is normally enough for the flow 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 width and nose radius.
Typical simulation runs were 15 per rim design and CFD run times of 6,000 hours for each rim.

2.2 Rim Shape

The two general design philosophies are split into V2 and V3, with the V2 being an iteration upon the existing 42 LGA with the widest point on the rim being roughly halfway down the section. This design has been used primarily in road wheel development and offers the best performance with narrower road tyres. This philosophy has been transferred across to gravel wheels and has been used to develop wheels with low drag. However, profiles of this shape work best when the rim is wider than the tyre and this will not be feasible as gravel tyres get ever wider.

The V3 Rim family instead has the widest section of the rim on the hook of the rim and the rim narrows to the nose from there. The concept of this rim is to design around a 40/45mm tyre where it is accepted the widest point in the system will be on the tyre and to use the rim to make the most of this to make a tail to the aerofoil that is made by the rim and tyre.

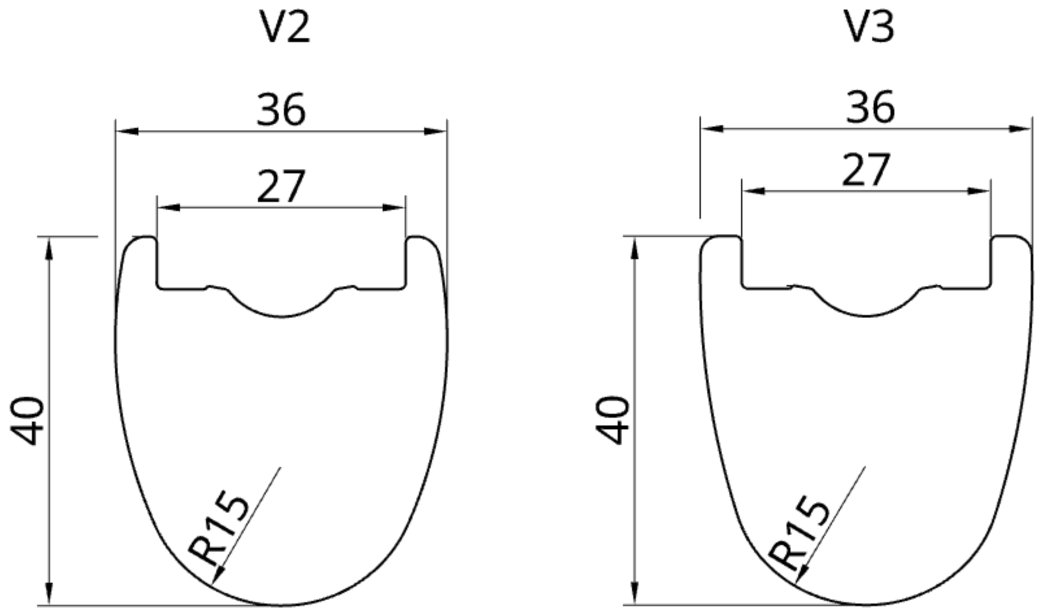

Figure 1- V2 and V3 Rim design features.

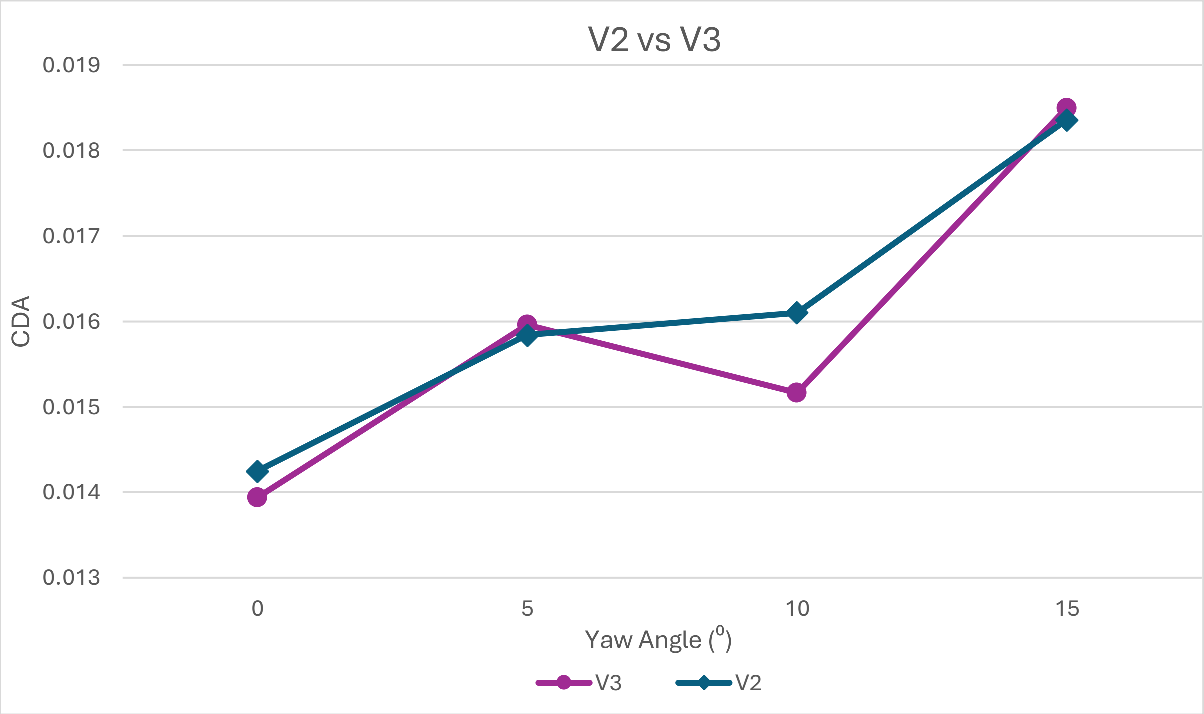

Figure 2 - Profile V2 vs V3 tested from 0 to 15 degrees

The V3 Profile was slightly faster due to the performance at 10 degrees. To illustrate the differences between these profiles, see figure 1 and 2 where it is visible from the visualisation of the flow velocity to see the reduction in turbulence behind the leading edge as well as a reduced area of slow speed air behind the trailing edge.

There is not a large difference between the two profiles as they are still very similar, but the V3 shape also borrowed structural features present in mountain bike wheels and would be preferable due to its wide flat flanges.

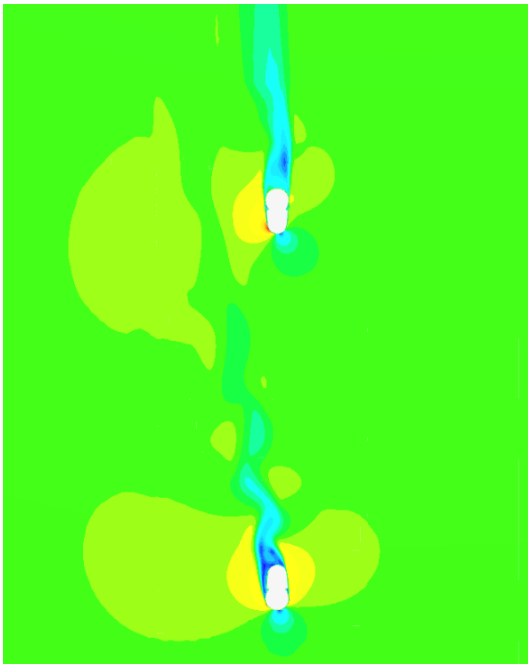

Figure 4-V2 at 10 degree

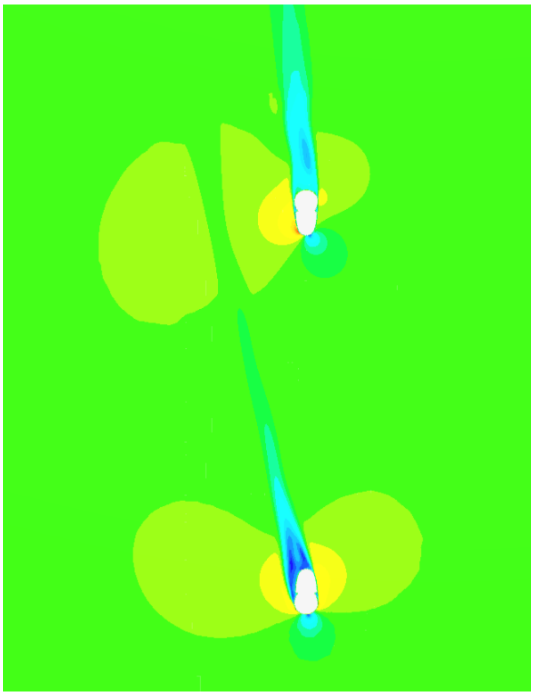

Figure 3 - V3 10 degree

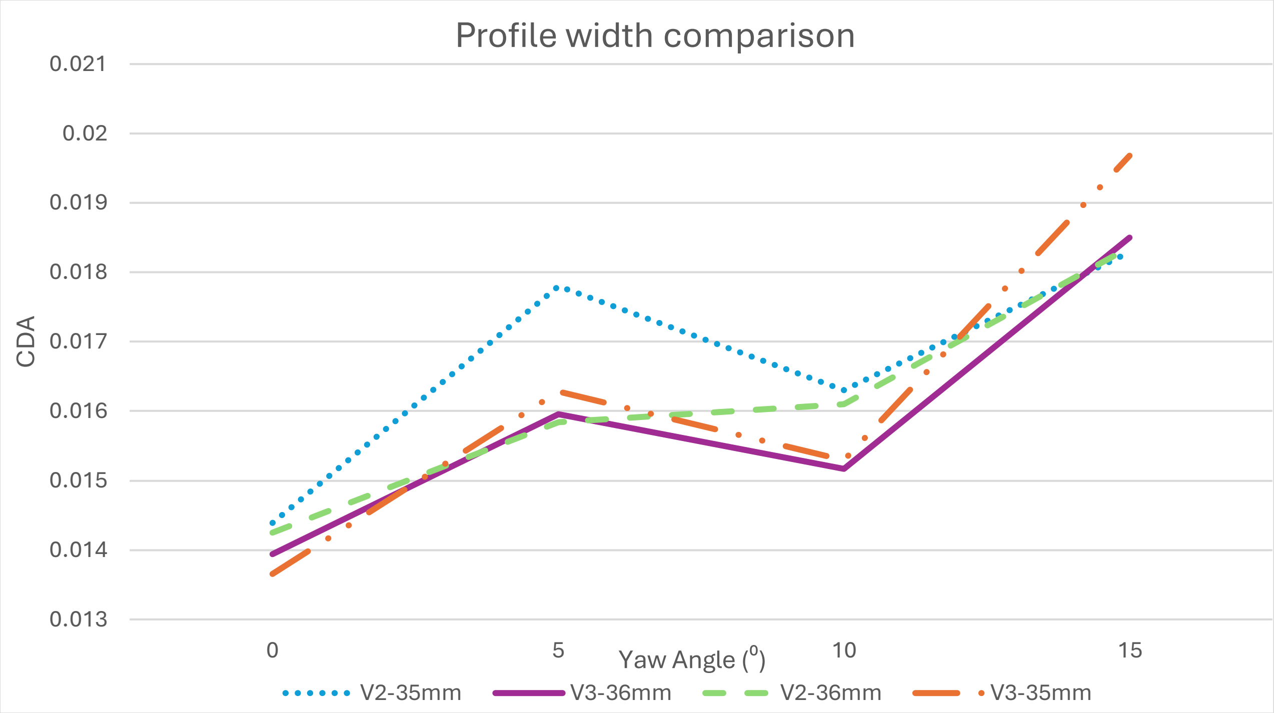

Figure 5 Profiles V2 and V3 at different widths

For both profiles, the 35mm profile was slower across the range of yaw angles. The V3 profile was less sensitive to width, with the V3-35mm profile having the best zero yaw drag performance of this set. These wheels were then tested in the full bike configuration.

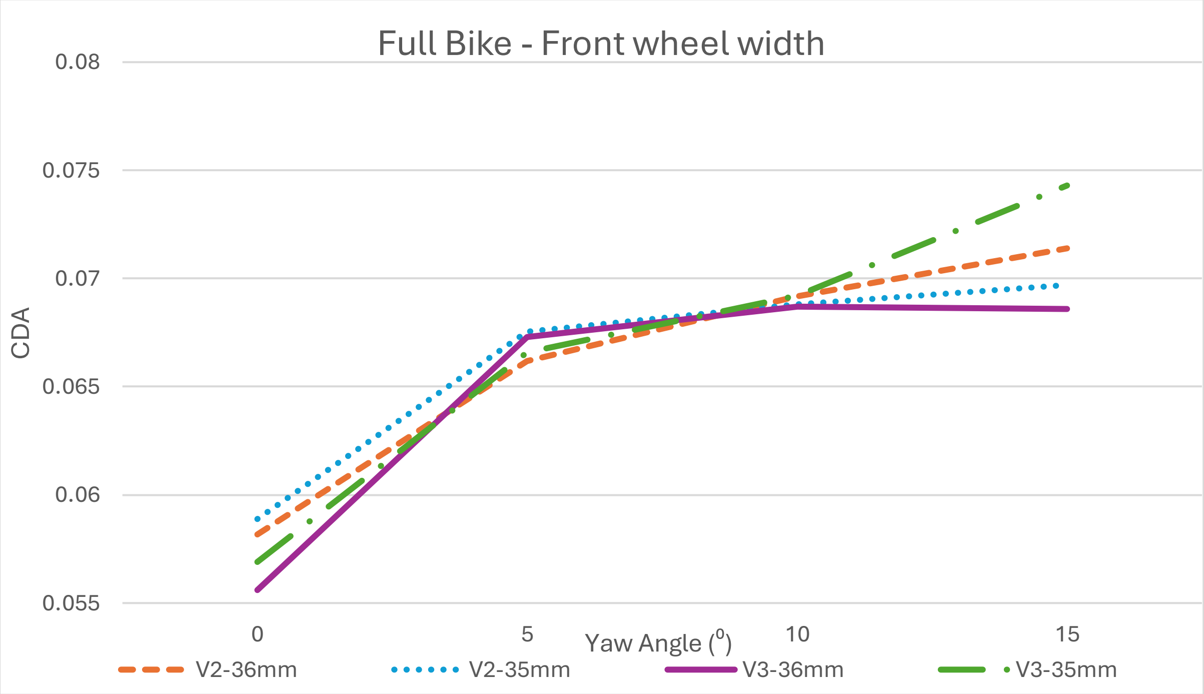

Figure 6 - Front wheel testing in full bike

The pattern is very similar in the full bike, with the 36mm wide profiles being faster when all yaw angles are considered, with the V3-36mm being the fastest, offering the best zero yaw performance while being competitive at middle to higher yaw angles.

The consistency of the V3 outperforming the V2 was sufficient to make the decision to progress with the V3 profile for further optimisation.

2.21 Front Profile optimisation

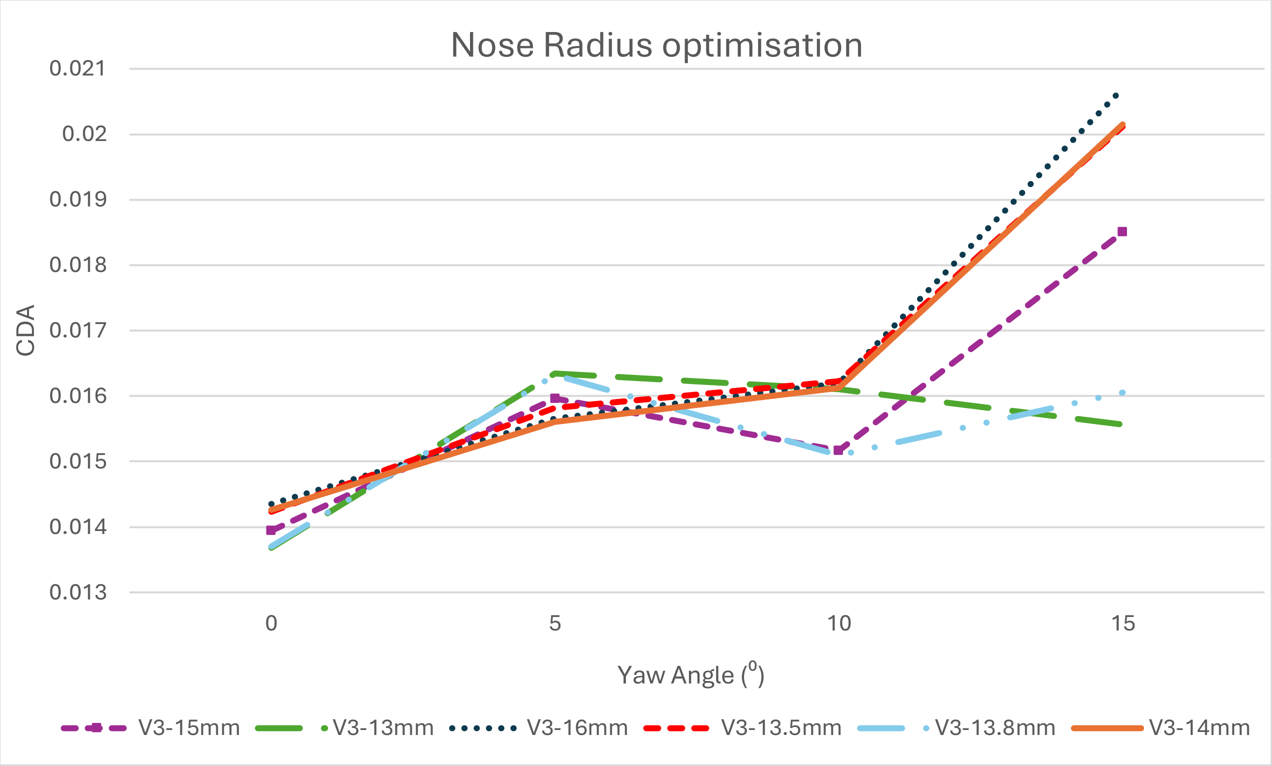

Figure 7 - wheel only, nose radius testing.

The 13.8 mm nose radius provided the best overall performance across the full range of yaw angles. With the best low yaw performance and very competitive high yaw performance outweighing its poor performance at 5 degrees. This also shows signs of transferring well to the wind tunnel where measurements are taken to 20 degrees.

The profiles selected to be taken forward to the first wind tunnel test were the V3-36mm-R13.8, a 35 mm wide version of this profile and the fastest of the V2 rim profiles, which was the 36 mm wide rim. This was to validate the simulation results and was a shape closer to rims that have previously tested faster.

2.3 Rear Profile Development

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 most the profile’s performance.

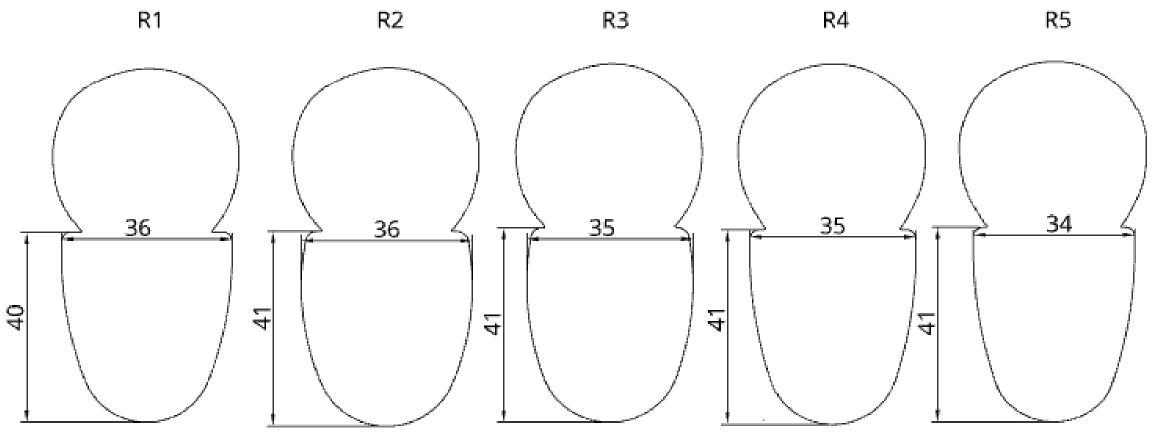

Figure 8 – Cross sections of early rear rim versions tested in full bike simulations.

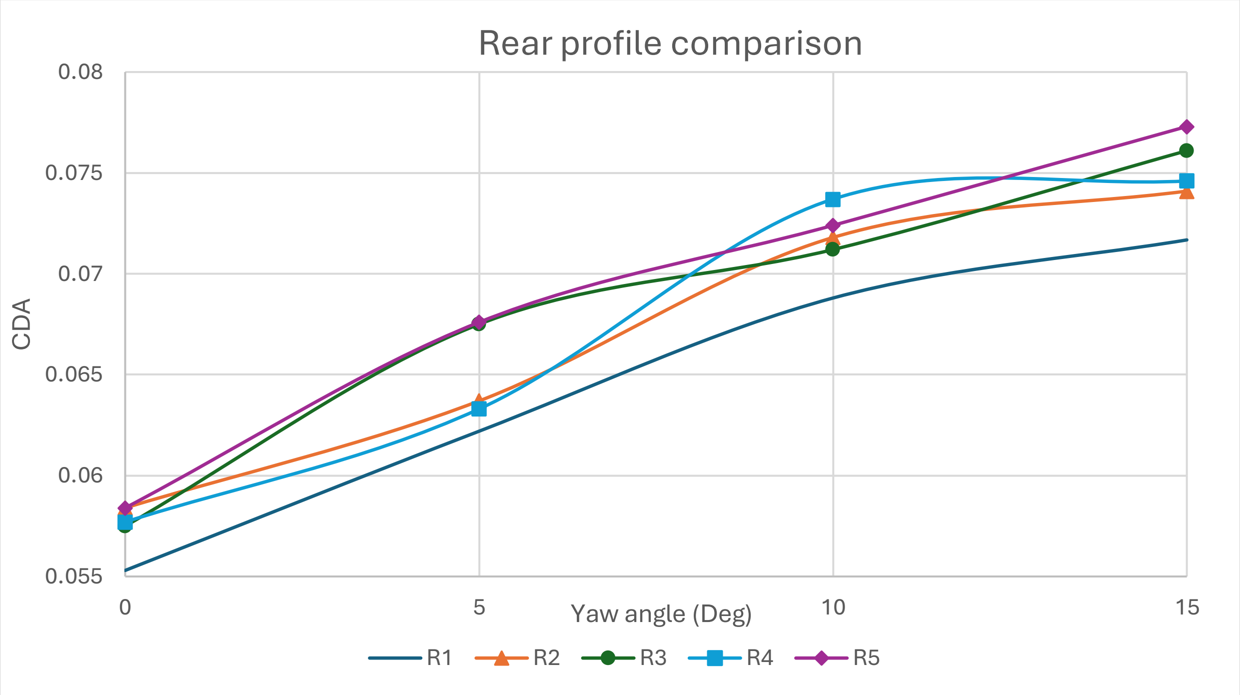

Figure 9 - Simulated full bike drag comparison 0° - 15°, demonstrating the effect of different rear profiles on CdA

For all these simulations there was a very large uncertainty making it hard to draw any strong conclusions from this study. However, the R1 was consistently the fastest profile on test so this was chosen to be taken to the wind tunnel.

The R2 profile although joint second fastest was eliminated and not taken forward as it was indistinguishable from the R3 and wider, so heavier. Hence the R3 was preferred. R4 and R5 were taken forward to allow us to study the effect of wheel width on drag and to provide data on narrower rim profiles to test if this was a viable option, to again reduce the rim weight.

3.0 Creation of wind tunnel Prototypes

The wind tunnel prototypes were produced in-house at HUNT with the help and support of Formlabs.

Figure 10 - Wind tunnel prototype wheel.

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.

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 the one section with a valve hole. The rims were then built into wheels, trued and tensioned.

4.0 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.

Figure 11 - Prototypes rims at the wind tunnel waiting to be tested.

Figure 12 – Open Up used for 2024 wind tunnel testing

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.

3D printed prototype wind tunnel setup:
Bike: Scott Addict Gravel (56 cm)
Tyres: Schwalbe Pro G-One Allround 40mm and Schwalbe G-One R 45mm
Tyre Pressures: 30 psi for all carbon wheels
Wind and Roller Speed: 45 kph
Yaw Angles: -20° to 20°.

Final production test setup:
Bike: Open Up. (Large)
Tyres: Schwalbe Pro G-One Allround 45mm and Schwalbe G-One R 40mm
Tyre Pressures: 30 Psi
Wind and Roller Speed: 40 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 a full bike and of swapping bikes very easily 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 very small differences in drag to be picked up between runs, but the controlled environment does still lose some realism.

4.1 Selection of competitor wheels

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

- Wheelsets that are marketed as gravel capable and are a company's premium offering in this market sector, ensuring a fair comparison with wheels designed for similar purposes and tyre sizes.
- Approximately 40 mm in depth, this is where most aerodynamic gravel wheel offerings are. This is similar to the depth of the 40 LGA.
- Internal rim width within +/-3 mm of the 40 LGA: with an internal rim width of 27/26, this meant that all competitors were between 30 to 23mm wide. This is a large range and does effect tyre profile. But are all in the range of what would be considered reasonable gravel internal dimensions.

5.0 Results

5.1 Front Prototype testing

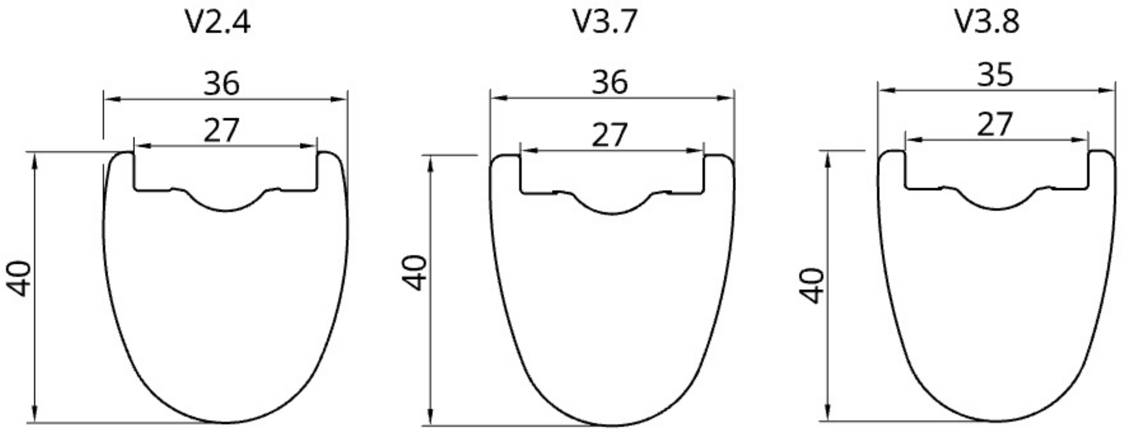

Figure 13 - Front profiles chosen to test at the wind tunnel

Table 1 - Results of prototype testing with 45mm tyres.

Front wheel	Rear wheel	Tyre	Measured width (mm)	Power Mavic WAD* (W)
V2.4	42 LGA	G-One R 45	44.47	120.56
V3.8	42 LGA	G-One R 45	44.72	120.57
V3.7	42 LGA	G-One R 45	44.72	120.64
42 LGA	42 LGA	G-One R 45	42.98	121.64
DT Swiss GRC 1400 SPLINE	42 LGA	G-One R 45	43.01	121.74

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

With the 45mm tyre all the prototypes tested very well, offering a large step in performance over both DT Swiss and the 42 LGA, and were very tightly grouped to each other and not outside the measurement uncertainty of 0.3 watts.

During the tests the tyre measured very wide on the 3D printed rim. This will be a result of the wider internal rim width, but also the plastic rim construction creeping as the testing progressed.

Figure 13 shows where the 3D printed prototypes separate their performance from the production rims, with more efficient performance at the higher yaw angles, above about 10 degrees we see a significant reduction in drag. The DT Swiss wheel is slower than all of the other profiles which are aerodynamic performance of these wheels is closely grouped for these wheels in the region between -8 and +8 degrees yaw with the only a outlier being the DT Swiss that has higher drag.

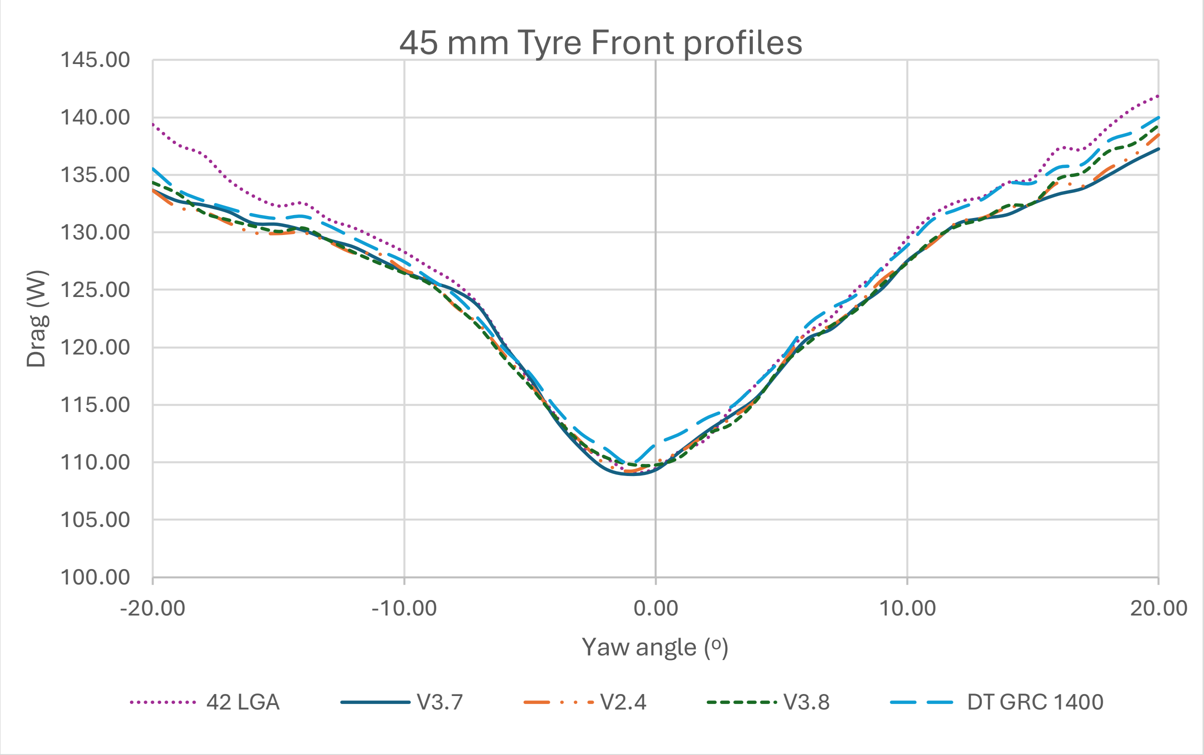

Figure 14 - Graph showing the aerodynamic performance of front prototypes with a 45mm tyre.

Table 2 - Results of prototype testing with 40mm tyre.

Front wheel	Rear wheel	Tyre	Measured width (mm)	Power Mavic WAD (W)
42 LGA	42 LGA	G-One Allround 40	38.41	112.56
V3.7	42 LGA	G-One Allround 40	39.62	113.11
DT Swiss GRC	42 LGA	G-One Allround 40	38.28	113.31
V2.4	42 LGA	G-One Allround 40	40.02	113.38
V3.8	42 LGA	G-One Allround 40	39.72	113.50

With a 40mm tyre the 42 LGA is the fastest profile by 0.6 watts with the rest of the profiles being tightly grouped behind. From figure 14 there is no clear differentiation between the drag profiles, as these are a small spread of results. The 42 LGA performs well across the full range and has a little separation from 2-8 degrees which is what leads to the reduction in drag, making it the fastest profile.

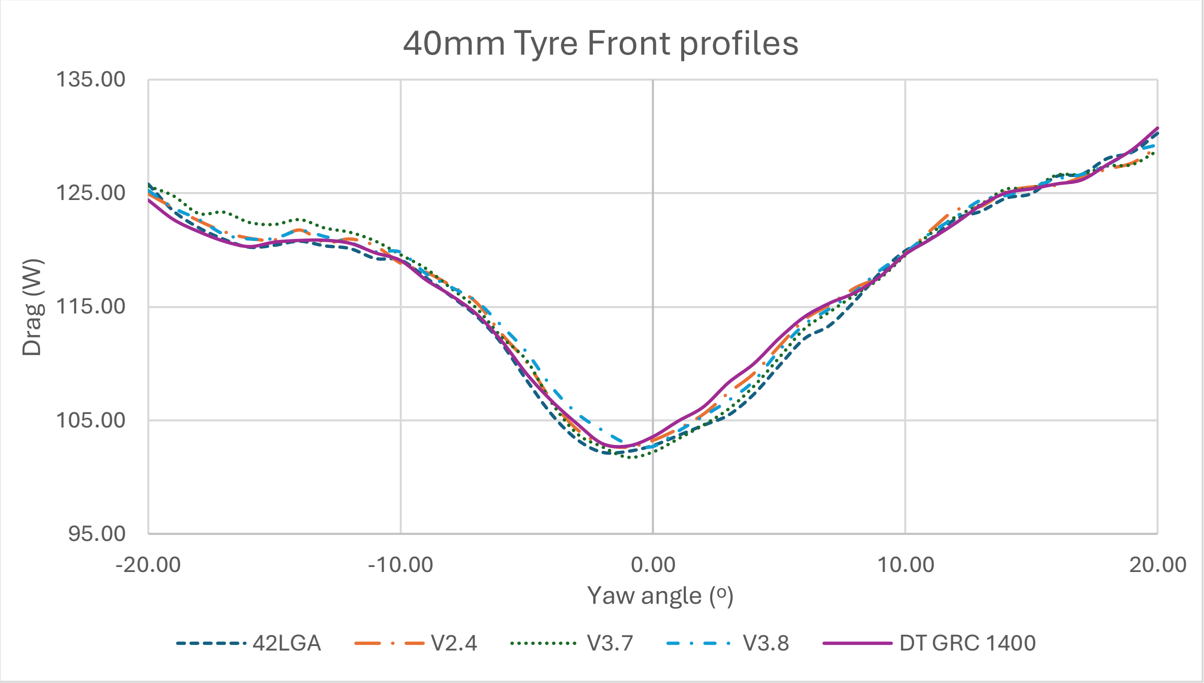

Figure 15- Graph showing the aerodynamic performance of front prototypes with a 40mm tyre.

5.2 Rear Prototype testing

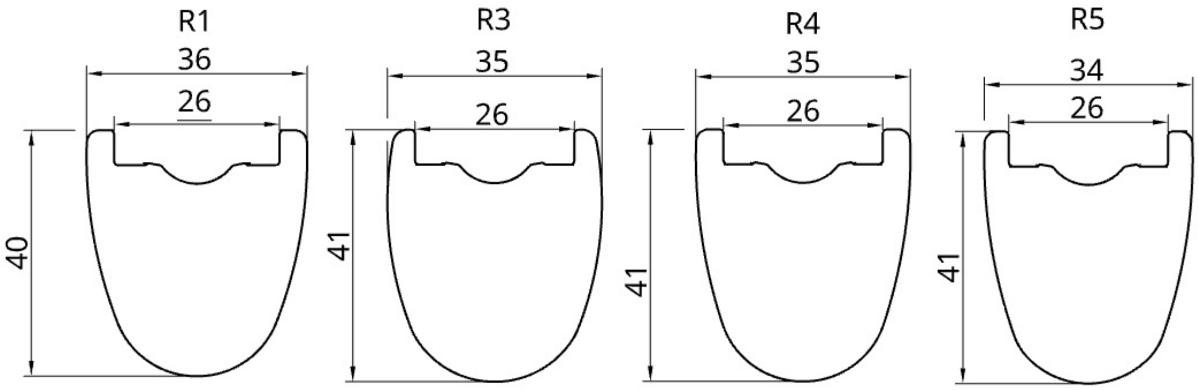

Figure 16 - Prototype testing, of all the wheels taken showing the drag from -20° to 20° with a 30mm tyre.

Table 3 - Results for rear prototypes with 40mm tyre

Front wheel	Rear wheel	Tyre	Measured width (mm)	Power Mavic WAD (W)
42 LGA	42 LGA	G-One Allround 40	38.35	112.56
42 LGA	R4	G-One Allround 40	38.37	113.46
42 LGA	R3	G-One Allround 40	39.35	113.74
42 LGA	R1	G-One Allround 40	39.11	114.08
42 LGA	R5	G-One Allround 40	38.96	114.15

Once again with the 40mm tyre we see the 42 LGA proving to be a very fast profile with the narrow tyre size. There is a step in performance to the R3 and R4 profiles with little to separate them, showing a 35mm rear profile offers good aerodynamic performance with a 40mm tyre, with the R3 being very impressive considering how wide the tyre was measuring.

The wider, shallower R1 and narrower R5 are then grouped together a little further behind showing both profiles are a little less efficient. Figure 16 shows the separation that the 42 LGA achieves at higher yaw angles, managing to sail above 10 degrees. This will be helped by having the narrowest tyre profile leading to less disturbance in the flow at higher yaw angles where the rear wheel will start to see cleaner air flows.

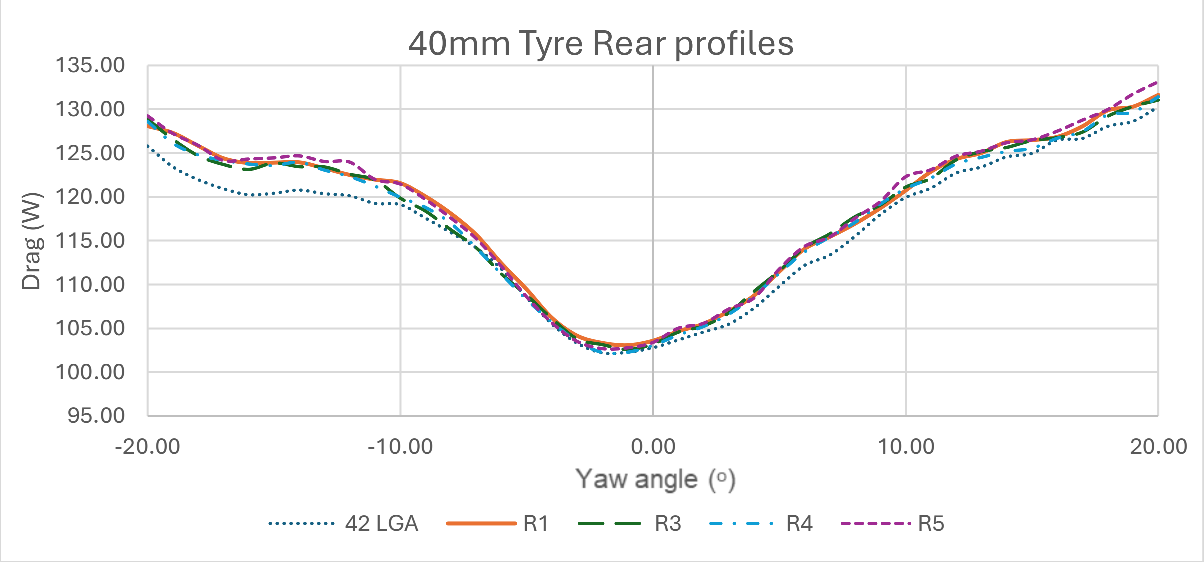

Figure 17 - Graph showing the aerodynamic performance of rear prototypes with a 40mm tyre.

Table 4 - Results for rear prototypes with 45mm tyre

Front wheel	Rear wheel	Tyre	Measured width (mm)	Power Mavic WAD (W)
42 LGA	R1	G-One R 45	42.91	119.45
42 LGA	R4	G-One R 45	42.60	119.94
42 LGA	R3	G-One R 45	44.05	120.10
42 LGA	R5	G-One R 45	44.00	121.14
42 LGA	42 LGA	G-One R 45	43.71	121.64

We again see the R3 and R4 profiles being very close to each other, which is to be expected with their profiles being the same width and depth, even with a change in fitted tyre width.

he R1 profile with its wider profile reduced the drag slightly, and in Figure 17 it is shown that this is due to the low yaw performance, this is likely due to the way the wider more V-shaped rear rim is fairing the tyre on the trailing edge of the wheel. The R5 profile again was the slowest prototype tested, only narrowly edging out the 42 LGA.

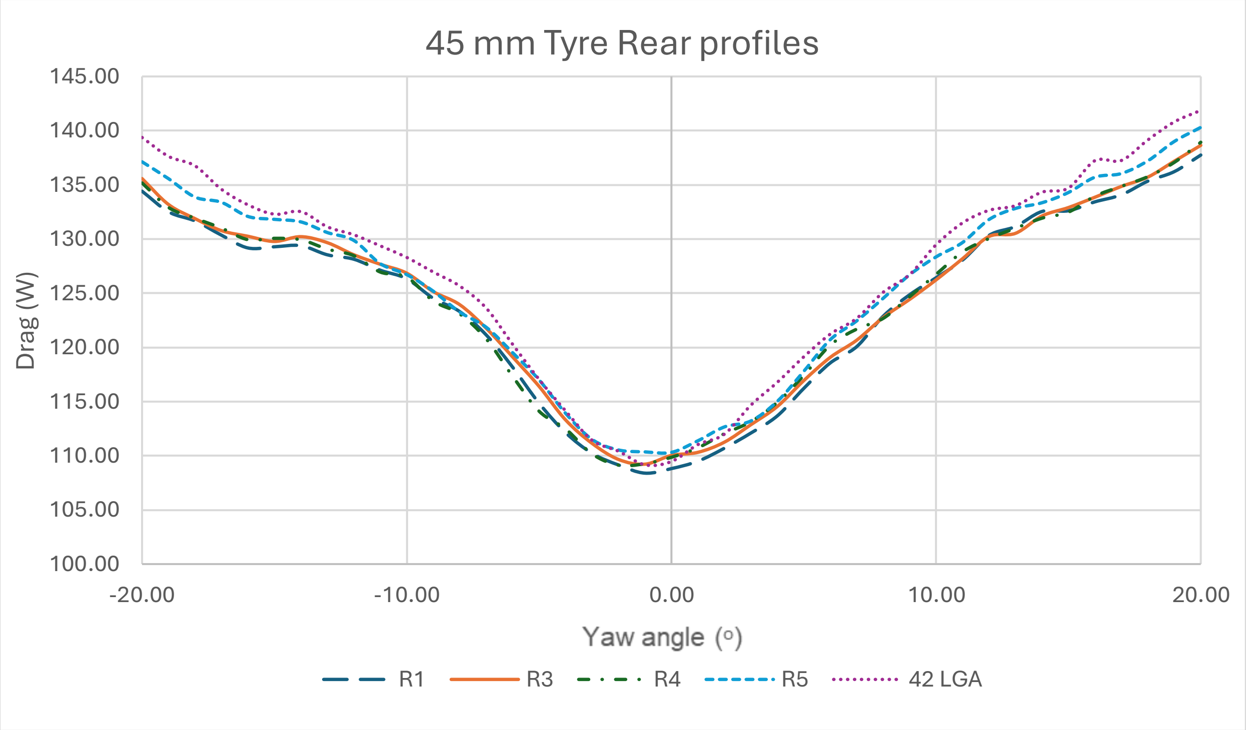

Figure 18 - Graph showing the aerodynamic performance of front prototypes with a 45mm tyre.

6.0 Selection of final rim designs

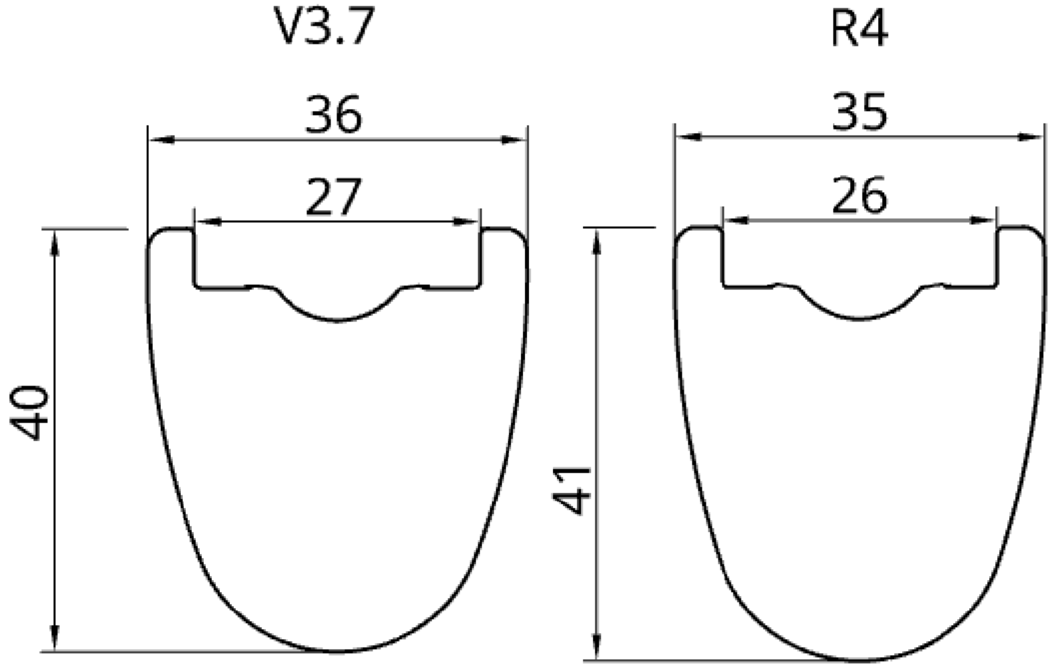

Figure 19 – Cross section of finalised profiles for carbon prototype testing

The two profiles that were selected to be manufactured as carbon fibre prototypes were the V3.7 and the R4. V3.7 was chosen as it was the fastest prototype with the 40mm tyre, and with a 45mm tyre it was the slowest, however the spread of all the prototypes on the 45mm tyre was only 0.08 watts. The rear profile chosen was the R4 as it was the second-best profile with both the 40mm and 45mm tyre, and the fastest 3D printed prototype with the 40mm tyre. The two profiles also made for an ideal pairing, with both having the same wall thickness of 4.5 mm on each hook, which would deliver consistent pinch flat protection and impact resistance across both profiles.

7.0 Finished carbon fibre prototype wind tunnel results.

Table 5 - Results of 40mm Tyre WAD data

Wheelset	Power Mavic WAD (W)	Nominal tyre size (mm)	Measured width - F & R Averaged (mm)	Averaged depth (mm)	Claimed weight (g)
HUNT 42 LGA	95.78	40	40.55	42	1548
3T Discus 45/40	95.80	40	40.68	45	1665
HUNT 40 LGA UD	96.45	40	40.28	40.5	1328
DT Swiss GRC 1400 SPLINE	96.46	40	40.62	42	1634
ENVE 3.4 SES	96.48	40	39.77	41	1380
Reserve 40/44	96.50	40	40.68	42	1381
Zipp 303 Firecrest	97.83	40	40.01	40	1408
Zipp 303s	98.22	40	39.42	45	1530
Cadex 35 AR	98.45	40	39.78	35	1270

HUNT 40 GCR	98.51	40	39.68	40	1383
Roval Terra CLX-II	98.58	40	40.35	32	1250
Campagnolo Levante	101.25	40	39.86	30	1485
HUNT 4 Season Gravel Disc	105.47	40	40.33	19	1698

Of all the wheels tested the 40 LGA was the 3rd fastest with a 40 mm tyre, only beaten by the 3T discus 45/40 and the 42 LGA. These are two of the wider wheels on test with their widest point a reasonable distance from the hook, and test very well with the G-One R tyre with a medium side knob. Closely following this is another grouping of the wheels all above 30mm in width, all of which are offering similar aerodynamic performance. There is a big step to the Zipp 303 Firecrest, where the 30mm external width is leading to high drag in the tyre's wake.

From the Zipp 303s to the Roval we see a group of even shallower or narrower wheels that are showing even higher drag figures due their shapes being less optimal with this tyre.

The HUNT 4 Season Gravel Disc is a shallow alloy wheel placed in the table for reference, and has been removed from following graphs apart from when mentioned as it makes the data hard to read, as expected it is a significant outlier.

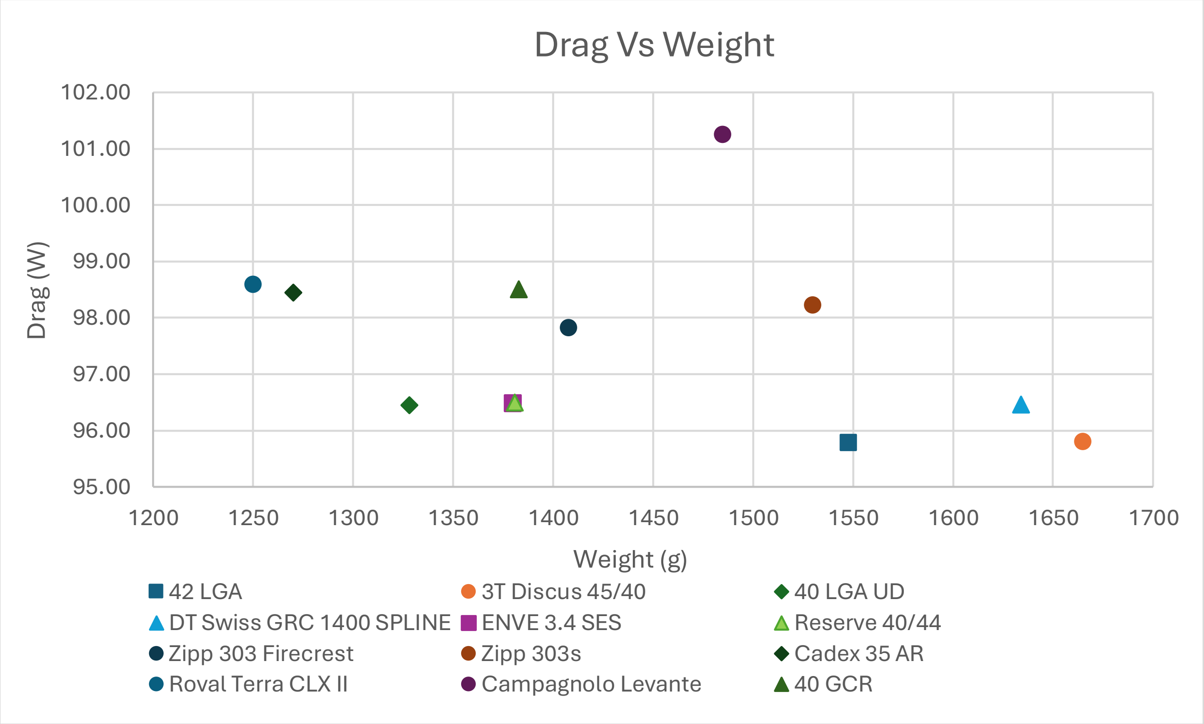

Figure 20 - Drag compared to wheelset claimed weight, with a 40mm tyre.

Figure 19 shows that wheels in general are getting more aerodynamic as they get heavier, which is to be expected as deeper and wider wheels will likely be more aerodynamic, but this requires more material to achieve and hence higher weight.

The wheels offering the greatest aerodynamic performance for their given weight are the 40 LGA UD's, Reserve 40/44 and the ENVE 3.4 SES. They are giving up relatively little performance to the heavier wheels such as the 3T discus 45/40 and the DT Swiss GRC 1400 SPLINE, whilst saving up to 300g. The Campagnolo Levante and the Zipp 303s to a lesser extent, are poor for their weight in terms of aerodynamic drag.

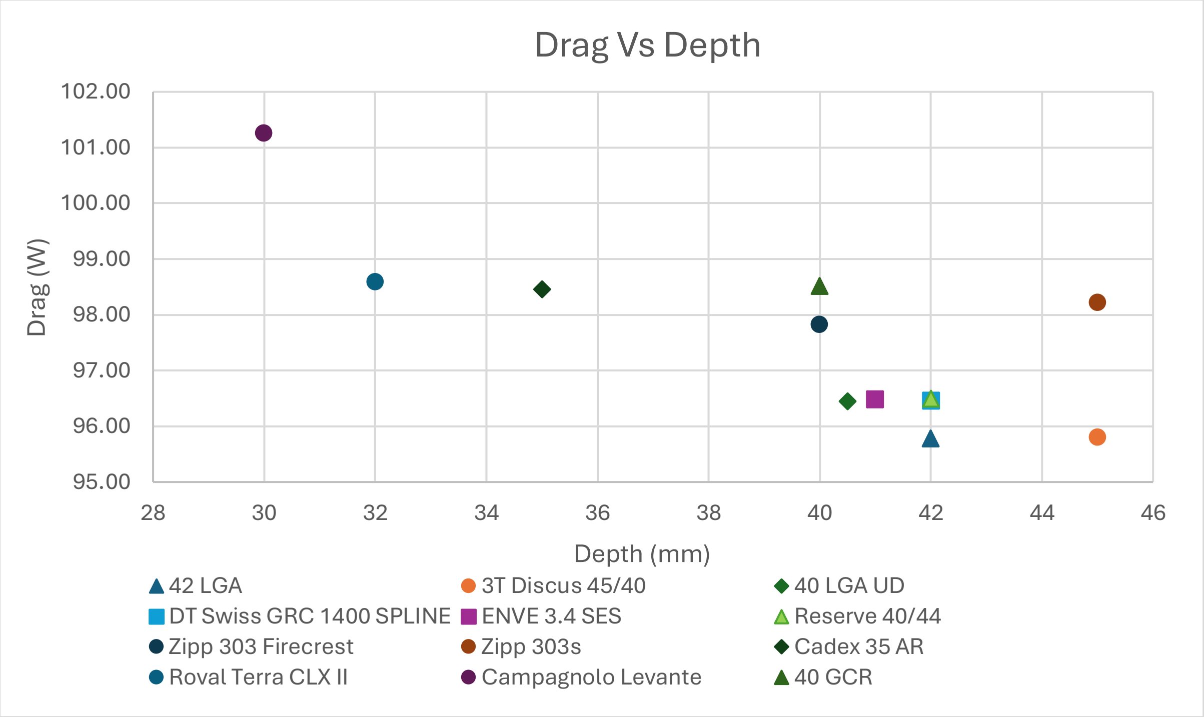

Figure 21- Drag compared to wheelset depth, with a 40mm tyre.

The depth of the wheels shows a trend where the deeper the wheel is, the more likely that it will have a low drag result. The outliers to the is trend are the Roval Terra that performs well for its depth and the Zipp 303s which is more of an all-road wheel and does not perform well in this test set up.

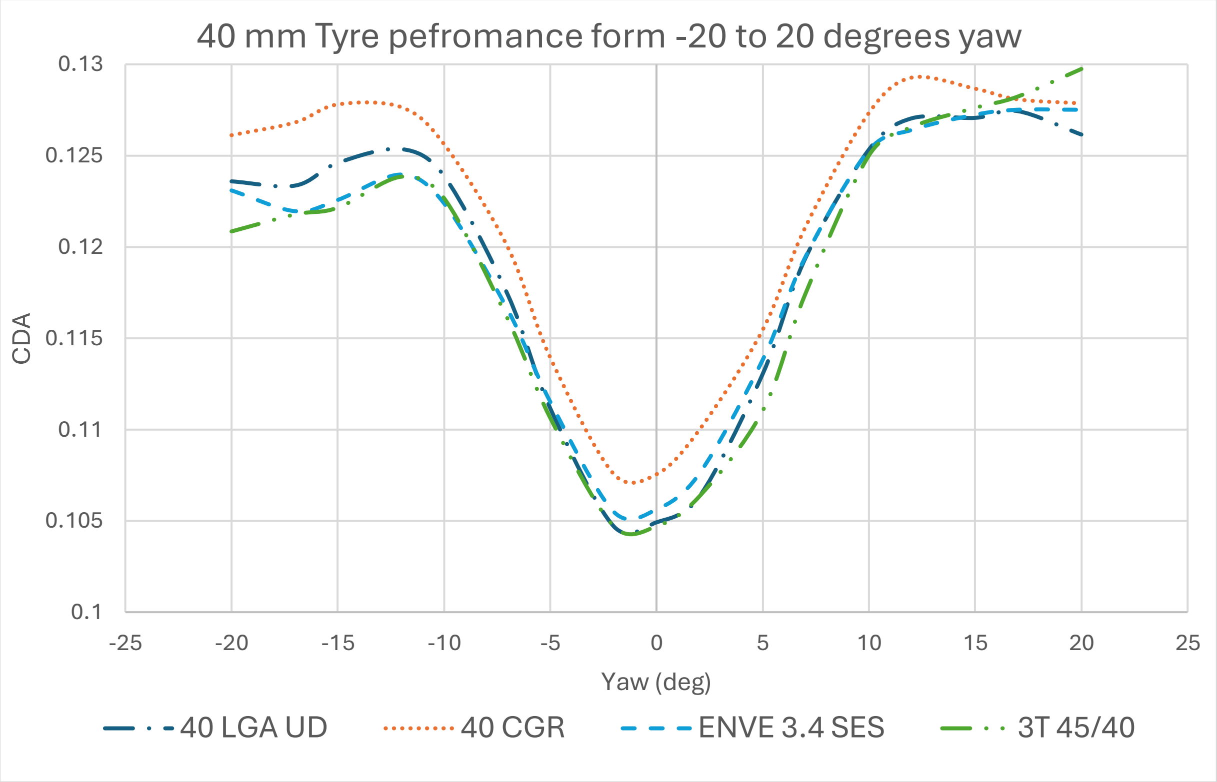

Figure 22- CDA with a 40 mm tyre measured from -20 to 20 degrees

Looking at the graph in figure 21, all of the wheels apart from the 40 CGR are very tightly grouped, and showing a similar performance across the graph, this is due to the tyre and frame driving the majority of the system drag. However there are some differences due to the change in wheels, the 40 LGA and 3T are the fastest between -5 and 5 degrees with the 3T discus 45/40 then being the fastest across above this point. The 40 CGR demonstrates what happens when a wheel isn't wide enough to work efficiently with a given tyre, there is no re-attachment of the flow and this turbulence from the wheel leads to a large increase in system drag.

The other striking thing about this graph is that the difference between wheels appears to hold very constant across the full range of yaw angles. This is notably different to road wheels that can have very different low and high yaw performances. This is likely due to the tyre tread causing separation immediately, and it is impossible to achieve a sailing effect and the wheel's performance is determined by its ability to minimise the effect of the turbulence.

Table 6 - Result of 45mm tyre WAD data.

Wheelset	Power Mavic WAD (W)	Nominal tyre size (mm)	Measured width - F & R Averaged (mm)	Averaged depth (mm)	Claimed weight (g)
3T Discus 45/40	94.81	45	44.32	45	1665
HUNT 40 LGA UD	95.16	45	43.80	40.5	1328
HUNT 42 LGA	95.55	45	43.42	42	1548
Reserve 40/44	95.71	45	43.57	42	1381
ENVE 3.4 SES	95.76	45	43.23	41	1380
DT Swiss GRC 1400 SPLINE	96.20	45	43.05	42	1634
HUNT 40 GCR	96.86	45	42.86	40	1383
Zipp 303 Firecrest	97.11	45	43.13	40	1408
Zipp 303s	97.47	45	42.45	45	1530
Roval Terra CLX-II	97.88	45	43.45	32	1250
Cadex 35 AR	98.08	45	43.58	35	1270
Campagnolo Levante	101.13	45	43.36	30	1485
HUNT 4 Season Gravel Disc	104.58	45	43.60	19	1698

A very similar pattern is shown in Table 6 to 5 where the deepest and widest wheels are the best performers, offering the lowest drag figures. The rankings are slightly flipped with this set up, with the DT Discus 45/40 having the lowest drag followed by the 40 LGA UD, with the 42 LGA in the group of wheels that perform well but not exceptionally. The 40 CGR heads up the group that is again over 1 watt behind the wider wheels.

8.0 Aerodynamic performance analysis

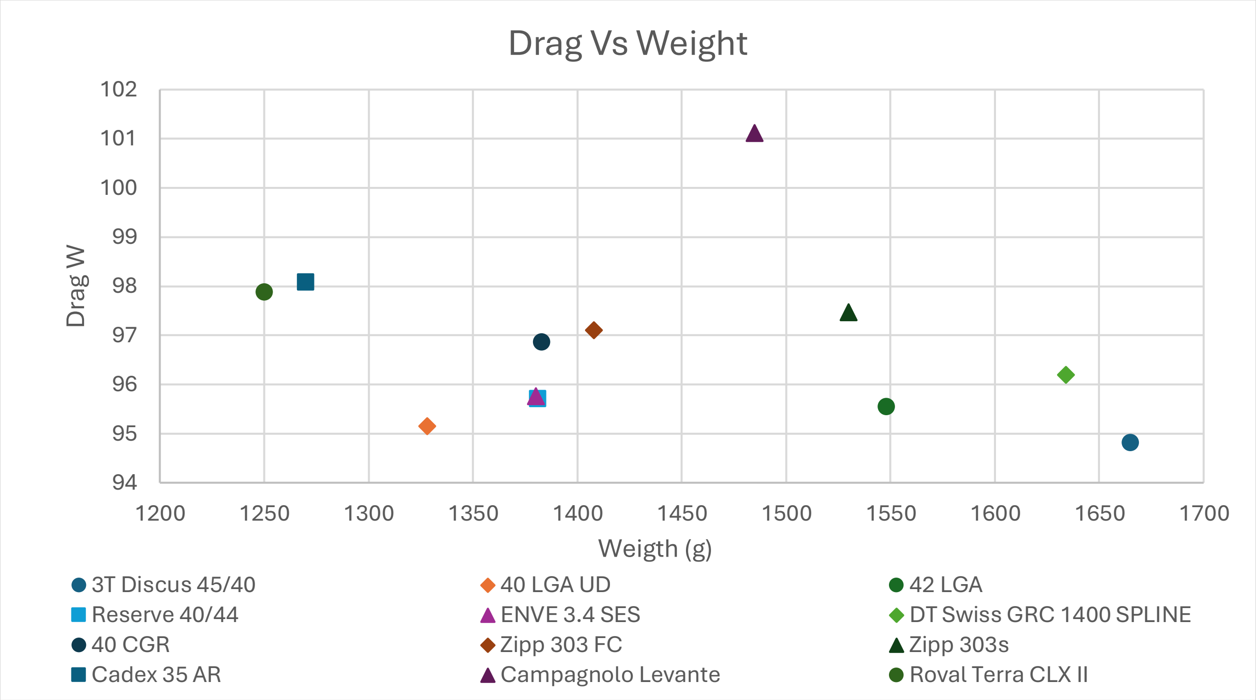

Figure 23 - Drag compared to wheelset claimed weight, with a 45mm tyre

Considering the drag to weight with this tyre, the wheel offering the best drag performance for the weight used in the rim is the 40 LGA UD, with a 300g weight saving over the only wheel faster than it on test and 53g gram reduction and 0.66 of a watt gain over the Reserve as the nearest competitor.

Apart from this increase in performance there is a very similar pattern to the one seen with the 40 mm tyre.

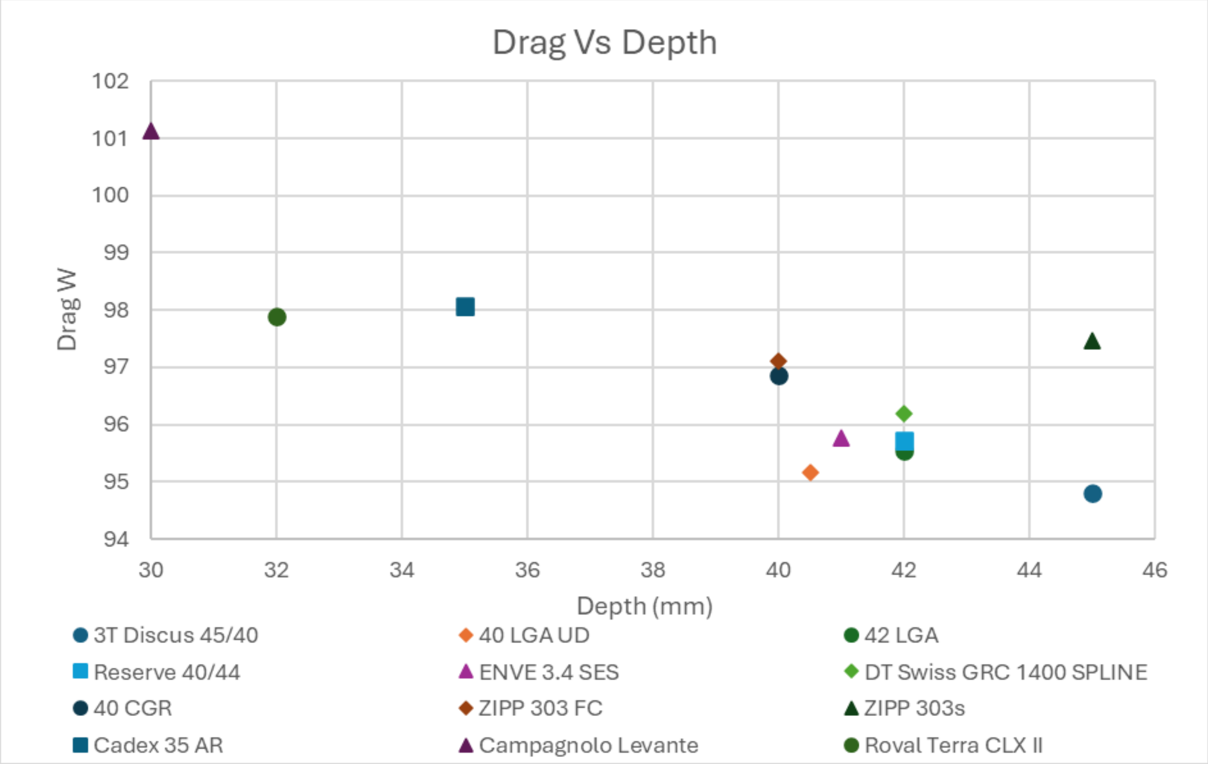

Figure 24 - Drag compared to wheelset depth, with a 45mm tyre.

Figure 24 shows the drag of a range of wheels, and the HUNT 4 Season Gravel Disc is plotted to show the very large drag offset to a shallow Alloy wheel, and it is obvious that it does not offer the same performance as any of the deeper carbon wheels, at low yaw it is closer but at higher yaw angles it just continues to produce more drag, compared to the rest of the wheelsets.

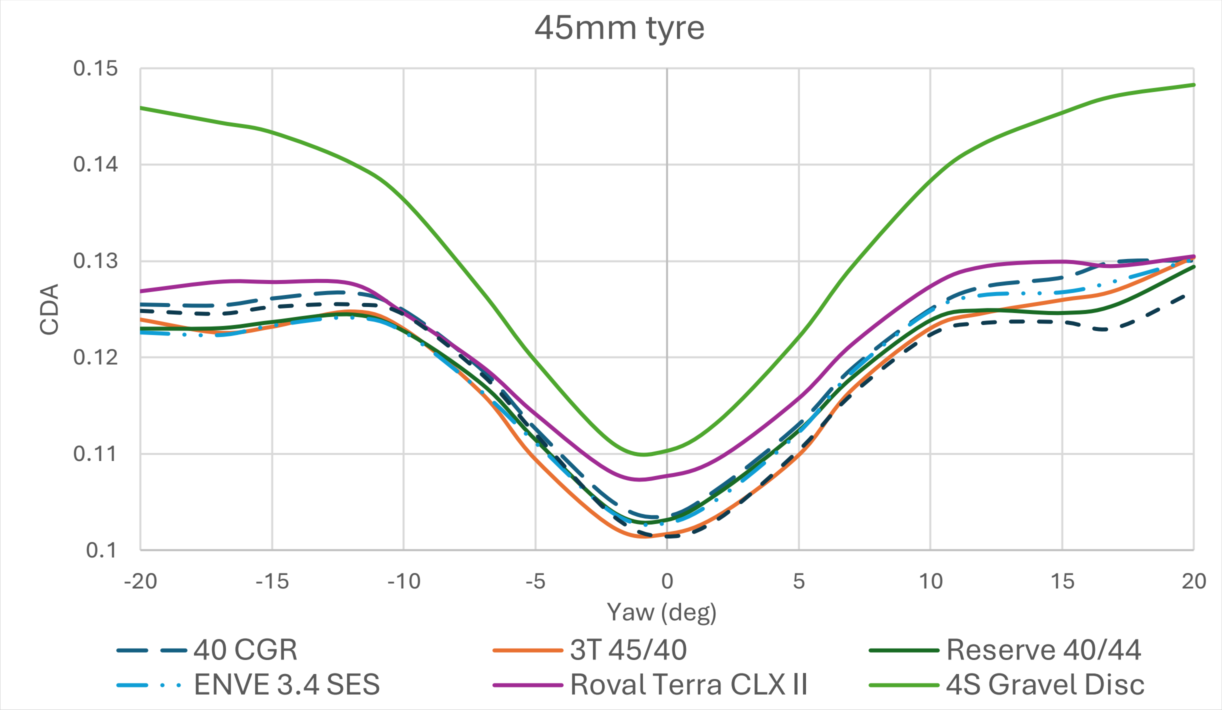

Figure 25 - CDA with a 45 mm tyre measured from -20 to 20 degrees

9.0 Conclusions

The aim of this project was to create a new wheelset building on the technological groundwork of the 42 LGA 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 gravel racing wheelset.

Compared to the 42 LGA, the 40 LGA UD reduced drag by 0.39 watts with a 45mm tyre and reduced overall wheelset mass by over 220g to 1328g for the carbon spoke version. In comparison to the leading competitors in the test:

- With a 45mm tyre the 40 LGA UD has the second lowest aerodynamic drag after the 3T discus 45/40 (0.34W difference). The 40 LGA UD had lower drag than the Reserve 40/44, DT Swiss GRC 1400 SPLINE and the Zipp 303 Fircrest (0.5W, 1.04W and 1.95 respectively)
- With a 40mm tyre the 40 LGA UD has the second lowest aerodynamic drag after the 3T discus 45/40 (0.67W difference). The 40 LGA UD had lower drag than the DT Swiss GRC 1400 SPLINE, Zipp 303 Fircrest and CADEX 35 AR (0.01W, 1.38W and 2.06 respectively).

- For an all-round gravel wheel, the 40 LGA UD offers the fastest overall package with both tyre sizes considered, but especially with the 45 mm tyre. The only wheel consistently faster than it, the 3T discus 45/40, has a 320g weight penalty. The 40 LGA is faster than both the ENVE 3.4 and Reserve 40/44, whilst also being lighter.

- The only wheels that are slightly lighter are the CADEX 35 AR and the Roval Terra CLX ii which are around 3 watts slower for a weight saving of 50 and 70g, which will not offset the aerodynamic wattage penalty on all but the very hilliest of courses.

The good aerodynamic performance and low wheelset weight, when paired together with wider internal rim widths to support the tyre and wide hooks to prevent pinch flats, leads us to believe that the 40 LGA UD is a significant step forward in our gravel wheels performance. This is the culmination of many years of work and feedback from some of the best gravel race athletes.

When this is twinned with the real-world testing performed by HUNT's Beyond and Gravel riders, and strenuous impact testing developed with our mountain bike product led us to believe we have made the best all round gravel wheel for riders who want to go fast on gravel.

10.0 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.

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 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.

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 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.

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

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.

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 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.

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.