TEST REPORT

Title:	Caden wheels WT test
Client:	Ben Cawood, Caden
Test lead:	BC, JP
Report author:	JP
Report version:	1
Report date:	20/06/2025

Test summary

- A range of competitor and feature development tests were performed in a 'bike&wheels-only' setup at a constant 50 km/hr speed, across a range of yaw angles. Wheels were rotating at 29km/hr ground speed.
- The tyre size was seen to be a dominant feature in the aerodynamic performance of the wheels tested.
- Overall, it was seen that having a rim width suited to the tyre is as important as maximising the depth (Scope is 65 vs. Caden 60mm, vs. Reserve front 53mm).
- With the narrower tyres (28 or 111 aero front, 30 rear) the Scope 6A slightly outperforms the Caden.
- With the hidden nipple feature, the Caden has equal performance with the Scope using the 111 Aero tyre.
- With the 30 and 32mm tyres, the Caden outperforms the Scope wheels, which is likely due to its greater external width (something that may be the cause of the slight penalty with the 28mm tyre).
- The Reserve wheels were generally ranked behind the Scope and Caden options in all cases.
- There was no apparent penalty for the Caden going from a 28 to a 30mm tyre on the front.
- All wheels generally had a ~1-1.5 W drag increase going from a 30 to a 32 front tyre.
- In terms of Caden development features, on reviewing the data it was concluded:
    - There was no measurable difference for the carbon spokes
    - Hidden nipples were a small (~0.5W) benefit on the front wheel only
    - Low spoke count with narrower hub flange was a similar (~0.5W) benefit also.
    - The custom drilled rims were a drag penalty vs. the standard rim.

ACSA wind tunnel test info

Test date(s)	18/06/2025
Tunnel facility	ACSA ¾ Open jet
Operator	RR
Return circuit air conditioning	ON
Nominal test speed(s)	50 km/hr
Yaw range	0, +/-7.5, +/-15°
Floor boundary layer suction	ON
Wheel rotation, resistance	Rotating, 8 m/sec
Recording methodology	ACSA LV v5
Images	Front/side/top camera images captured during each run

Setup info

Figure 1 - Bike setup

Figure 2 - Front end view

	Spokes	Nipples
Caden	Alloy elliptical	External
Reserve	Alloy elliptical	External
Scope 6	Carbon bladed	Internal
Scope 6A	Carbon bladed	Internal

Table 1 - Wheel feature list

Figure 3 - Scope 6 wheelset

Figure 4 - Scope 6A wheelset

Figure 5 - Scope front hub

Figure 6 - Reserve wheelset


Figure 7 - Current Caden 60 front wheel

Figure 8 - Caden hiddle nipple test wheel

Figure 9 - Caden low spoke count, carbon spoke hub test options

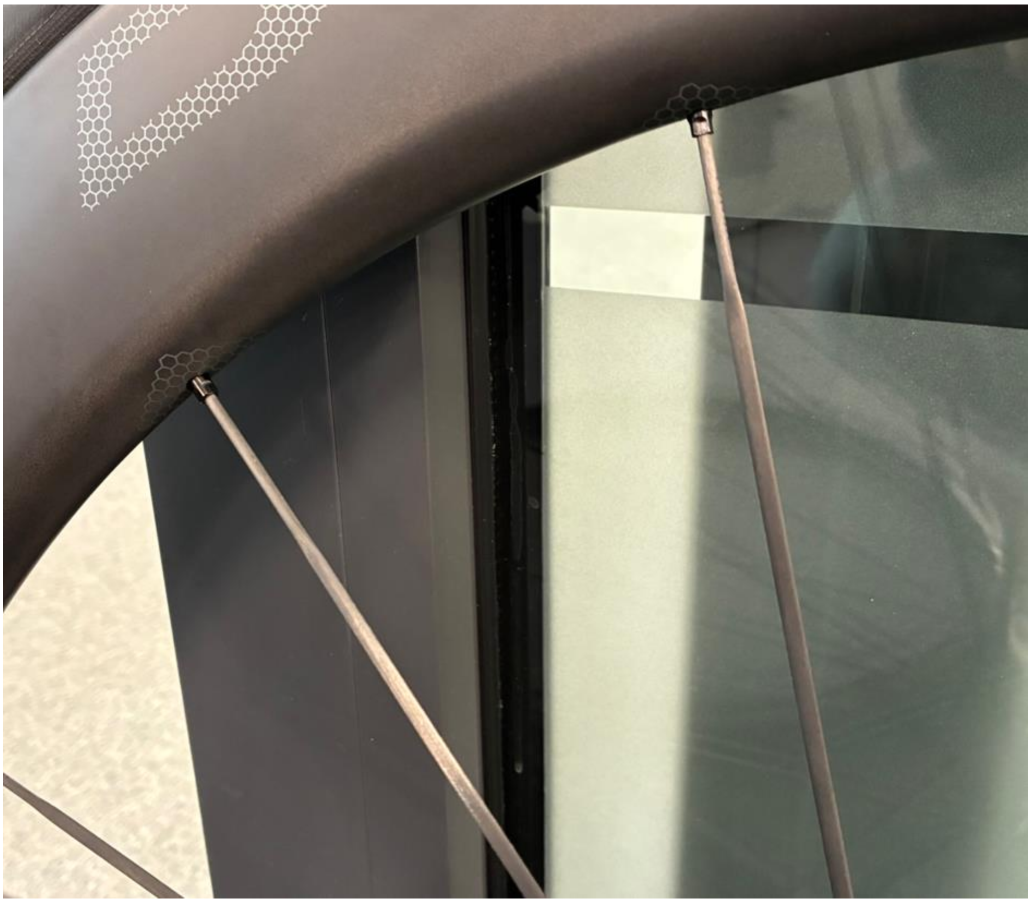


Figure 10 - Caden Carbon bladed spoke with semi-hidden nipples

Test protocol

- 50 km/hr wind speed. Represents Elite level fast road speed. Favourable for aerodynamic signal-to-noise ratio in wind tunnel
- Wheels rotating @ 8 m/sec ground speed (~29km/hr). Less than wind speed to avoid excess tyre heating and vibration.
- Yaw angles 0, +/-7.5, +/-15 degrees. Covers the typical range (see Appendix). Pragmatic balance in terms of # of points in yaw distribution vs. number of configurations required to be tested within the session.
    - Further future testing would likely increase the number of points in the yaw distribution to better assess performance around the stall region.

Results

Bike+wheels CDA, m^2. Strut tare removed

Speed, m/sec Yaw angle, deg	13.8000 -15.0000	13.8000 -7.5000	13.8000 0	13.8000 7.5000	13.8000 15.0000
1-shakedown_scope_28_30	0	0	0.0468	0	0.0417
2-scope_28_30	0.0369	0.0448	0.0469	0.0460	0.0419
3-scope_29_30_conti111	0.0283	0.0435	0.0468	0.0454	0.0317
4-reserve_28_30	0.0411	0.0455	0.0467	0.0464	0.0473
5-reserve_29_30_conti111	0.0304	0.0451	0.0464	0.0459	0.0349
6-scope6A_28_30	0.0358	0.0434	0.0466	0.0456	0.0430
7-scope6A_29_30_conti111	0.0269	0.0432	0.0465	0.0456	0.0314
8-caden_28_30	0.0415	0.0438	0.0464	0.0451	0.0444
9-caden_29_30_conti111	0.0277	0.0440	0.0474	0.0461	0.0326
10-cadenHN_28_30	0.0398	0.0433	0.0463	0.0439	0.0443
11-cadenLSCfr_28_30	0.0393	0.0436	0.0463	0.0446	0.0438
12-cadenPHfr_28_30	0.0436	0.0453	0.0469	0.0463	0.0472
13-cadenLSC_28_30_rpt	0.0386	0.0428	0.0460	0.0443	0.0440
14-cadenLSCfr_exRear_28_30	0.0388	0.0426	0.0461	0.0444	0.0446
15-cadenCarbonSpk_28_30	0.0415	0.0435	0.0468	0.0448	0.0454
16-scope_30_32	0.0400	0.0459	0.0474	0.0478	0.0416
17-scope_32_32	0.0385	0.0467	0.0482	0.0482	0.0410
18-reserve_30_32	0.0403	0.0462	0.0472	0.0474	0.0426
19-reserve_32_32	0.0376	0.0473	0.0478	0.0482	0.0458
20-scope6A_30_32	0.0336	0.0439	0.0473	0.0464	0.0407
21-scope6A_32_32	0.0340	0.0452	0.0478	0.0477	0.0429
22-caden_30_32	0.0324	0.0446	0.0475	0.0458	0.0389
23-caden_32_32	0.0350	0.0457	0.0478	0.0467	0.0417
24-cadenHN_30_32_frOnly	0.0389	0.0451	0.0475	0.0464	0.0372
25-cadenHN_30_32	0.0380	0.0452	0.0478	0.0466	0.0382
26-cadenCarbonSpk_30_32	0.0321	0.0442	0.0474	0.0457	0.0396
27-cadenHN_29_30_conti111	0.0278	0.0433	0.0467	0.0449	0.0310
28-scope6A_29_30_conti111_rpt	0.0263	0.0428	0.0465	0.0454	0.0314

Table 2

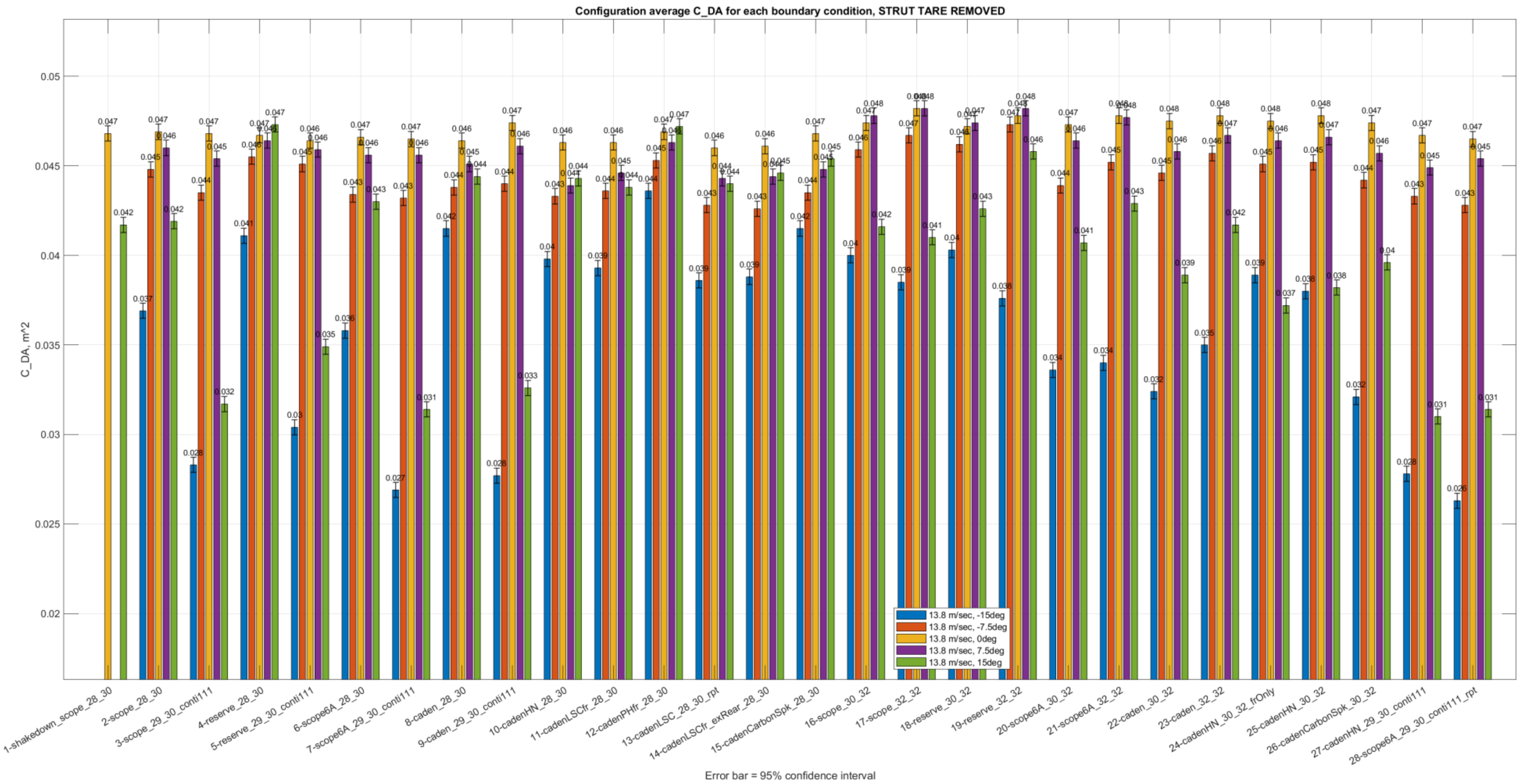


Figure 11 - Configuration average results – all runs

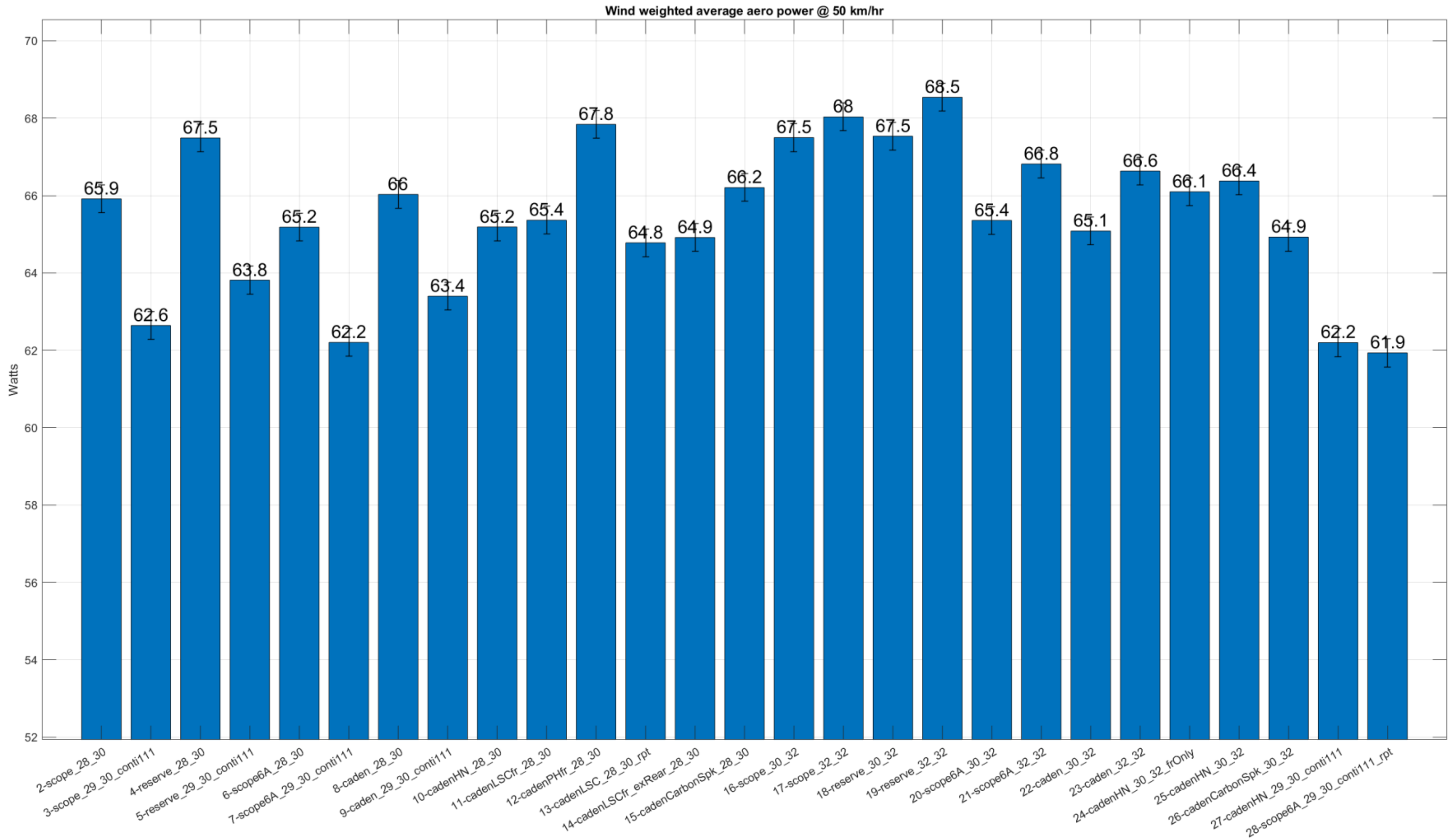


Figure 12 - Wind weighted average results (aero power). See appendix for weighting definition

Analysis and observations

Wind weighted average

- At the request of the client, the results on the day of the test were primarily reported as a wind-weighted average. This single-number metric is presented in equivalent watts required to overcome the aerodynamic drag at a defined speed and air density.
- For the definition of the wind-weighting values used, see the Appendix at the end of the report.

Repeatability

- The benchmark setup – Scope 6A with 29/30 tyre combination, was tested twice throughout the test – runs 7 and 28.
- As shown below, all the yaw-angle data point stdevs were less than 0.0005 CDA.
- In watts @ 50 km/hr, the yaw average is equivalent to a repeatability band of +/- 0.4W. This is used as the error bar in Figure 12. Any two runs where the error bars do not overlap are considered to be significantly different from each other.

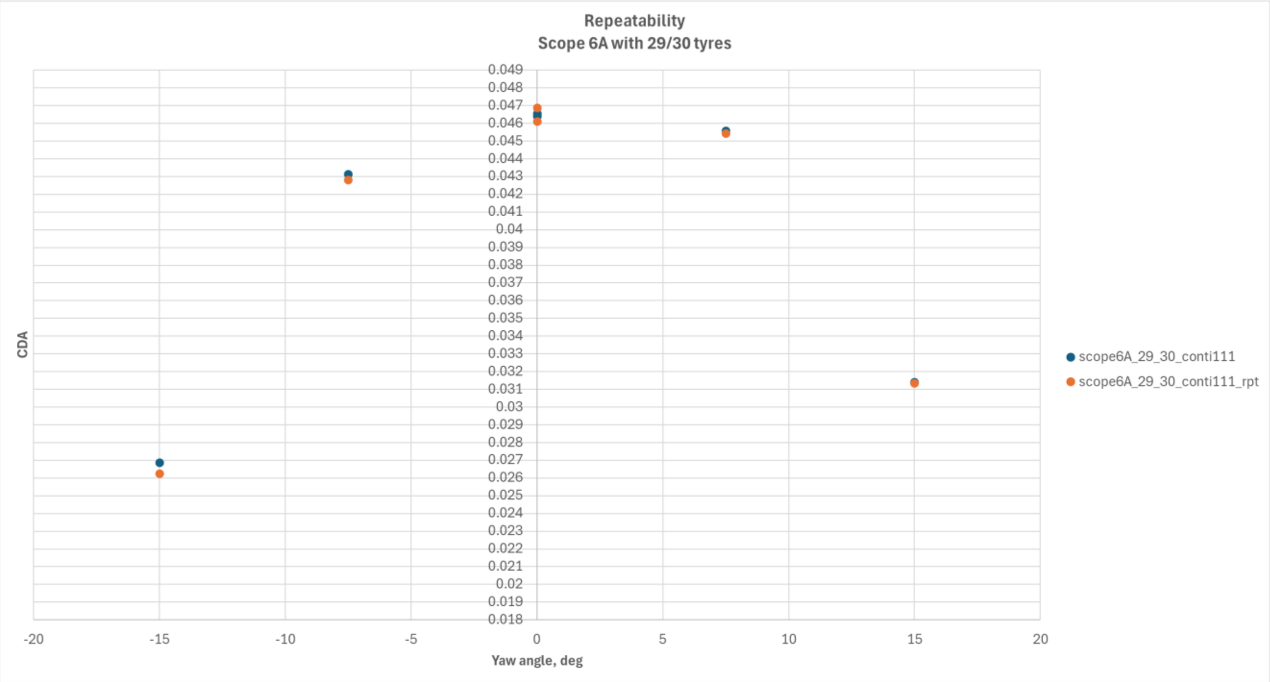


Figure 13 - Reference configuration repeatability

Tyre influence, comparison with competitors

- The following table reports the key measurements taken for each rim and tyre.
- Table 4 then presents the ratio between the rim width and tyre width for each front wheel combination tested. From past experience it is known that a pre-requisite to achieving good aerodynamic performance, particularly on the front wheel, is to have an outer rim width that is at least as wide as the tyre (ratio <1 = better).
- Of note is the fact that the Aero 111 tyre (Figure 14) measures the narrowest of all the tyres tested. This in addition to the dedicated vortex generating features that are moulded into the shoulder of the 111 makes it difficult to conclude which aspect contributes most to its performance.

Measurements in mm		Caden 60	Scope 6	Scope 6a	Reserve 52/63
Front	Outer width	34	30.8	33.3	34.8
	Inner width	25	23.2	25	25.8
	Depth	60	65	65	52
	GP5000 STR Tyre width 28	31.4	30	30.9	31.7
	GP5000 STR Tyre width 30	33.2	31.4	32.9	33
	GP5000 STR Tyre width 32	34.4	no meas	34	34.4
	GP5000 111 Tyre width 29	29.5	29.2	30.1	30.5
Rear	Outer width	34	30.8	33.3	33.9
	Inner width	25	23.2	25	24.7
	Depth	60	65	65	63
	GP5000 STR Tyre width 28	31.4	30	30.9	no meas
	GP5000 STR Tyre width 30	33.2	31.4	32.6	32.5
	GP5000 STR Tyre width 32	34.4	no meas	33.8	33.9
	GP5000 111 Tyre width 29	n/a	n/a	n/a	n/a

Table 3 - Rim, tyre measurements

Front wheel: Ratio tyre to rim outer width	Caden 60	Scope 6	Scope 6a	Reserve 52/63
GP5000 STR Tyre width 28	92%	97%	93%	91%
GP5000 STR Tyre width 30	98%	102%	99%	95%
GP5000 STR Tyre width 32	101%		102%	99%
GP5000 111 Tyre width 29	87%	95%	90%	88%

Table 4 - Front wheel tyre:rim width ratios

Figure 14 - 111 Aero tyre on Scope rim

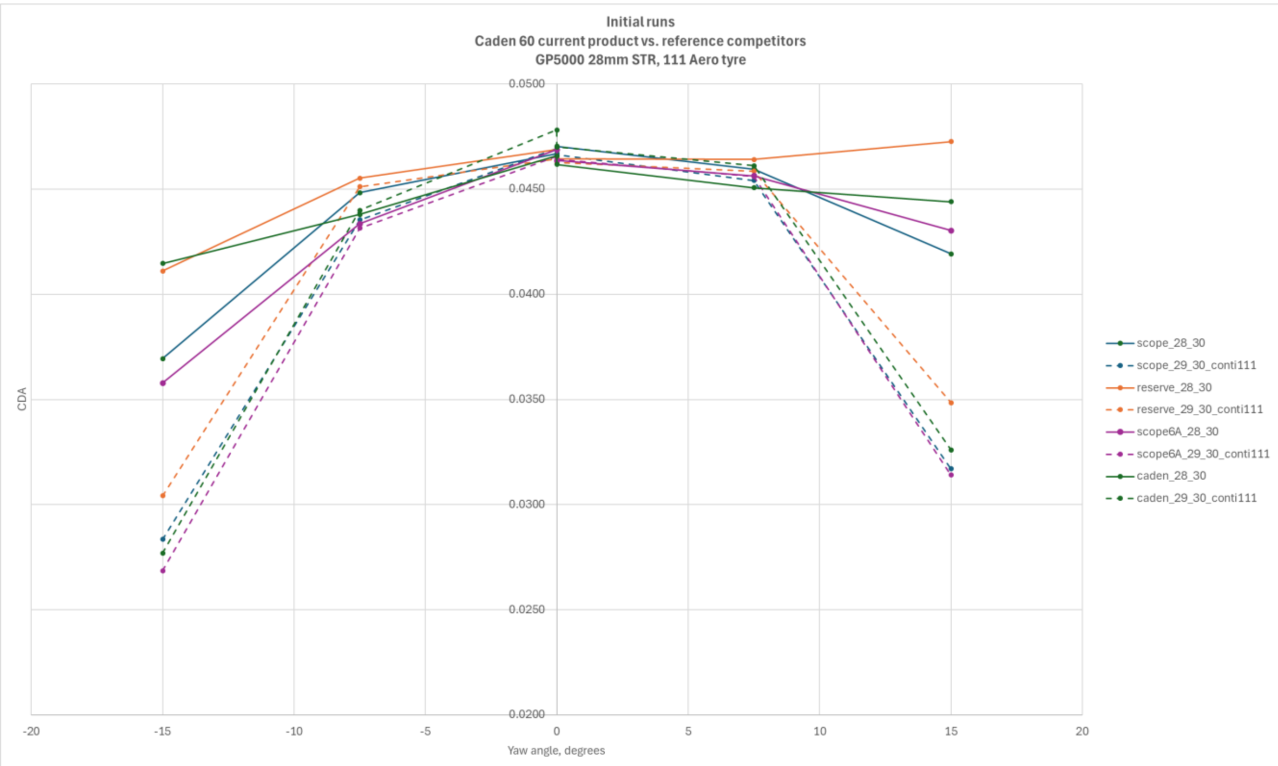


Figure 15

Figure 15 illustrates the strong influence the tyre has on the drag performance at higher yaw angles.
In each case the tyre effect is generally much larger than the rim effect. In general, the Reserve wheel performs the worst of those tested with both the 28 and 111 tyres, which is likely a reflection of the shallower front rim depth.
With the 28mm tyre the Scope and Caden wheels are similar to 7.5 degrees, then at 15 degrees the Caden appears to begin to stall, giving the Scope a modest overall advantage with this tyre using the weighted average.
With the 111 Aero tyre however the Caden and Scope wheels are identical in terms of performance across the range.

Figure 16 below shows the current Caden 60 wheel with all the tested tyre options.
Noteworthy here is the apparent worse performance of the 28 tyre vs. the wider 30 and 32 at the 15 degree yaw angles.
There could be several reasons for this, including:

- Better shielding of the rim join with the tyre for the 30 and 32
- More favourable interaction with the bike frame/fork due to the larger tyre sizes.

It would be desirable in a follow-up test to investigate these results with a greater number of yaw angle points, along with analysis of the side load, to help diagnose what is happening.

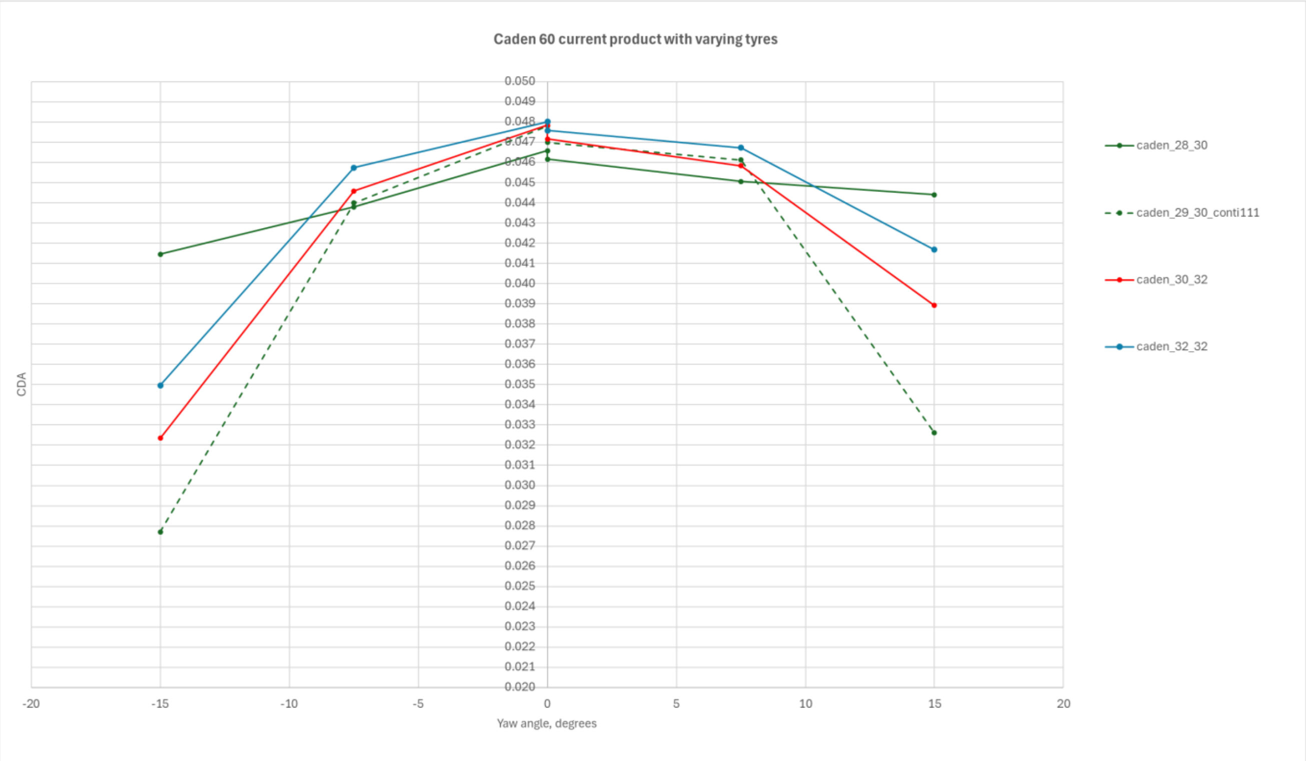


Figure 16 - Caden current 60 with all tyre options

- The relative width of the Caden rim (widest of those tested) begins to show clear benefits relative to the competitors when tested with the wider tyres as shown in the following figure.
- In all cases the 32mm front tyre measured slightly higher drag than the 30.

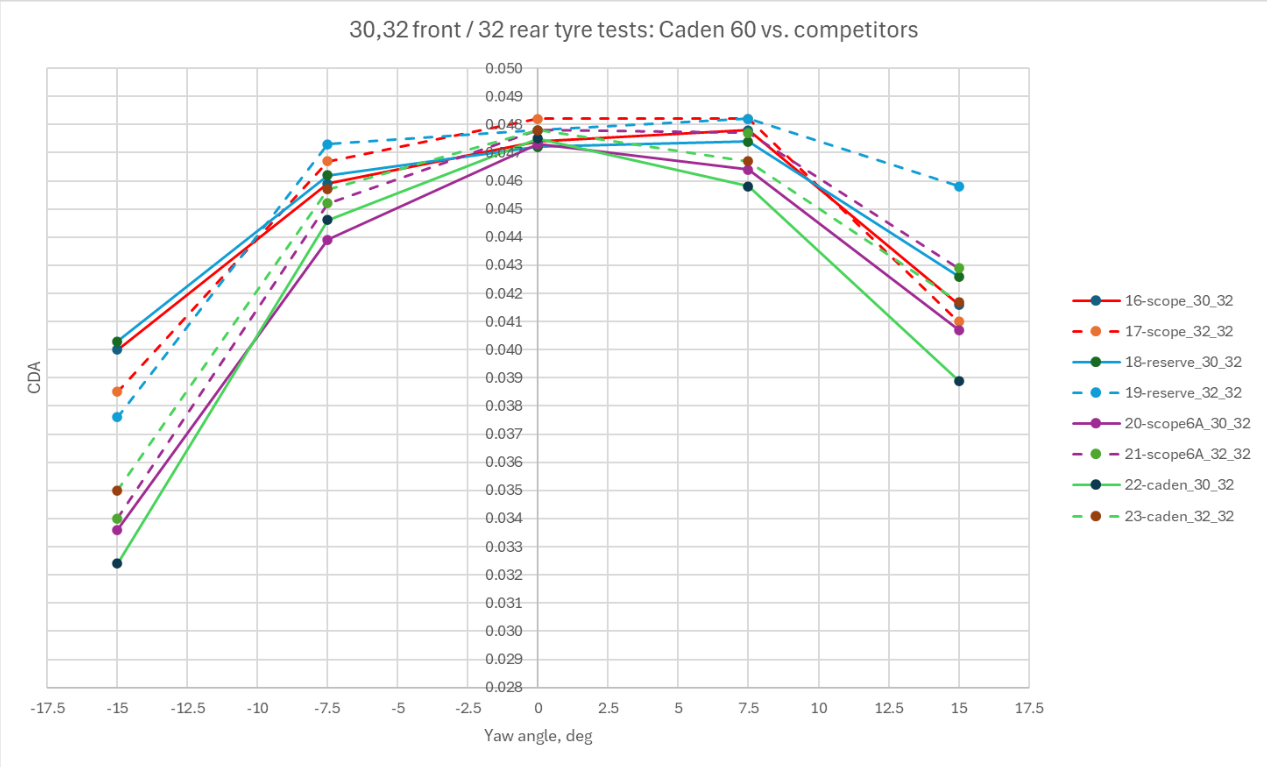


Figure 17 - 30/32mm tyre tests

Caden wheel feature tests

A number of alternative features were tested on the Caden 60 rim:

- Hidden nipples
- Low spoke count, with narrower hub flanges
- Carbon spokes
- Drilled rim

After a number of tests, it became apparent that at the +/-15° yaw angle that was chosen as the maximum, parts of the bike+wheels assembly were on the verge of stalling and a number of data points had a larger difference between configurations than was expected. As such, the average of the 7.5° data points (where the flow will be attached) for each configuration has also been used in this analysis (Figure 18) to help assess the performance of each feature.

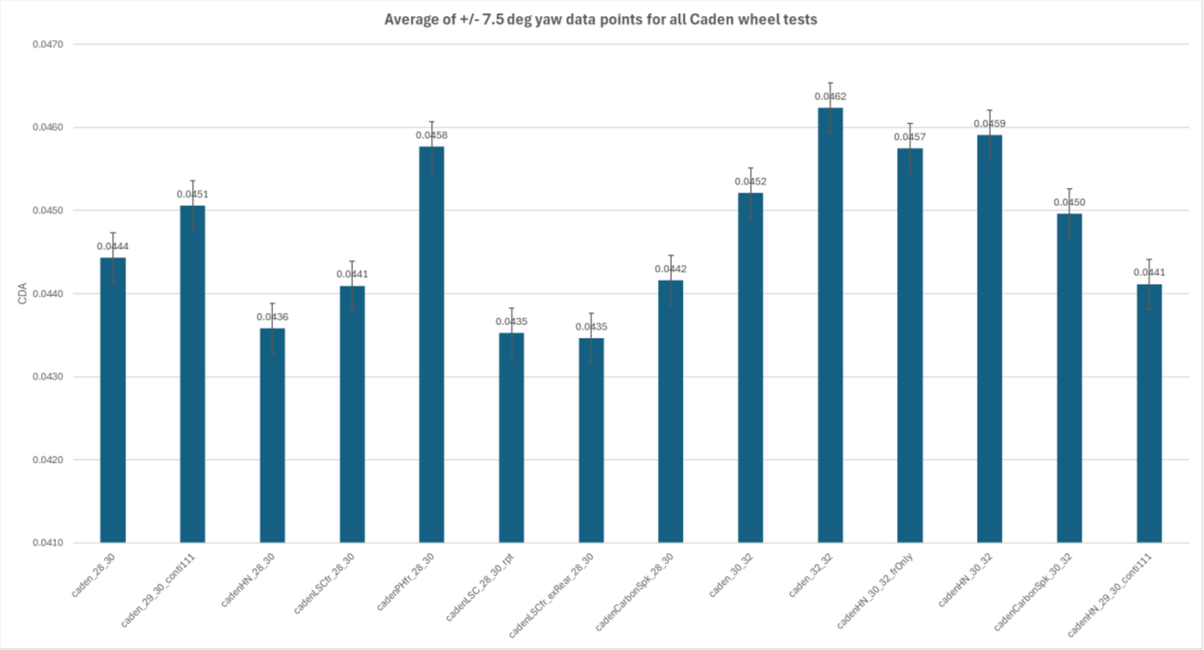


Figure 18

Hidden nipples

- Tested with three different tyres.
- Hidden nipples was a 0.001 improvement @ 7.5° for the 28 and 111 tyres
- Within the margin of error (overlapping error bars) @ 7.5° for the 30 tyre.
- From this it is suggested the benefit of the hidden nipples is on the order of the resolution of the test, i.e. up to 0.0005 m^2 CDA, ~0.2-0.8W @ 50 km/hr.
- Tests were also performed with the standard nipple configuration in the rear. There was consistently no influence of this, suggesting any benefit comes from the front only.

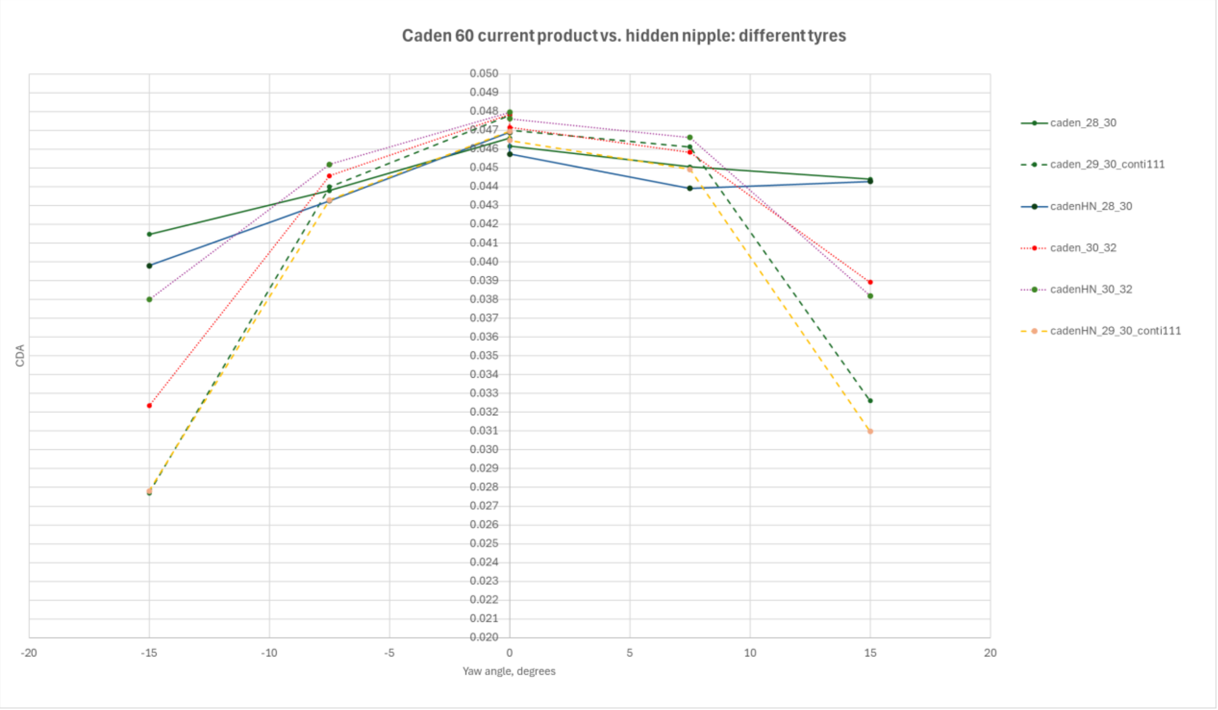


Figure 19

Carbon spokes

There was no measurable difference between the standard and carbon spokes when tested with the 28 or 30 mm tyres:

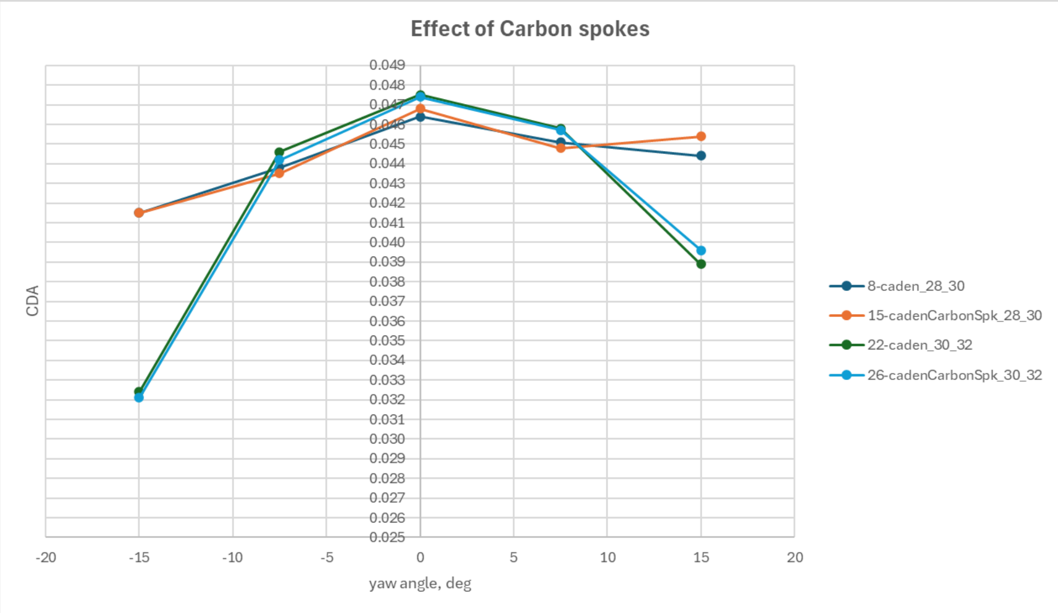


Figure 20

Low spoke count / hub spacing

- Does appear to be a benefit with the low spoke count, particularly at the -15 degree yaw angle. As with the hidden nipples, the gain is on the order of the resolution of the test, circa ~0.2-0.8W @ 50 km/hr.
- Expect this asymmetry is due to a combination of the seat-tube which has a differing profile relative to the rear wheel on either side (Figure 22) and the differing spoke dish on the front wheel. The corresponding asymmetry in the yaw-drag response helps confirm there is a small flow improvement occurring.

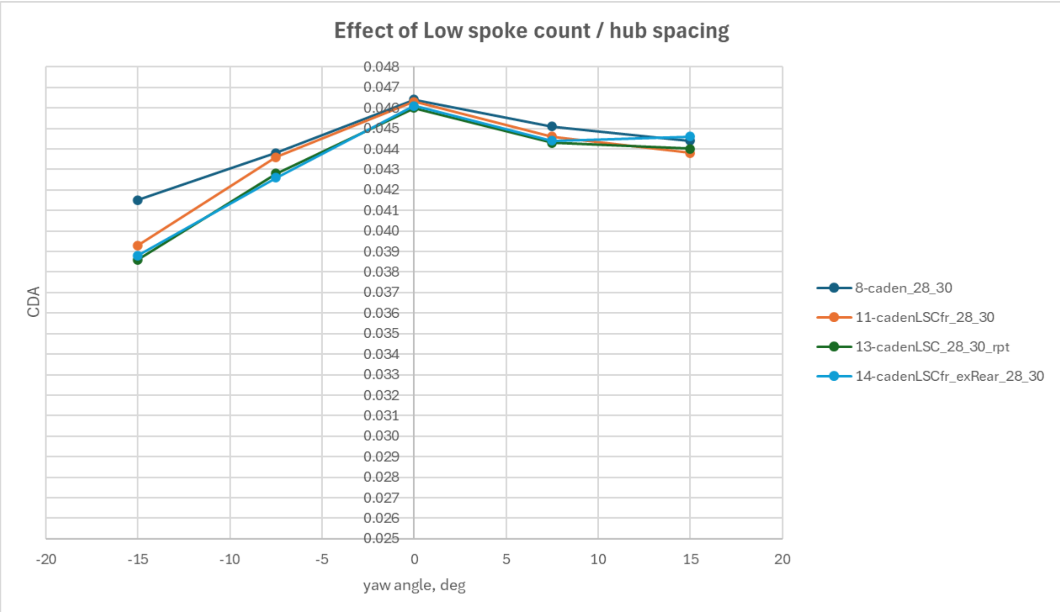


Figure 21

Figure 22 - Asymmetric seat-tube

Drilled rim

- The custom drilled rims were a small yet consistent penalty of ~0.001 CDA at all non-zero yaw angles when tested with the 28mm tyre.
- This is likely due to the positive pressure on the upwind side bleeding through and causing earlier separation on the downwind side.
- Ideally the flow would be ducted from the upwind side and re-directed tangentially toward the bike(drag) axis direction.

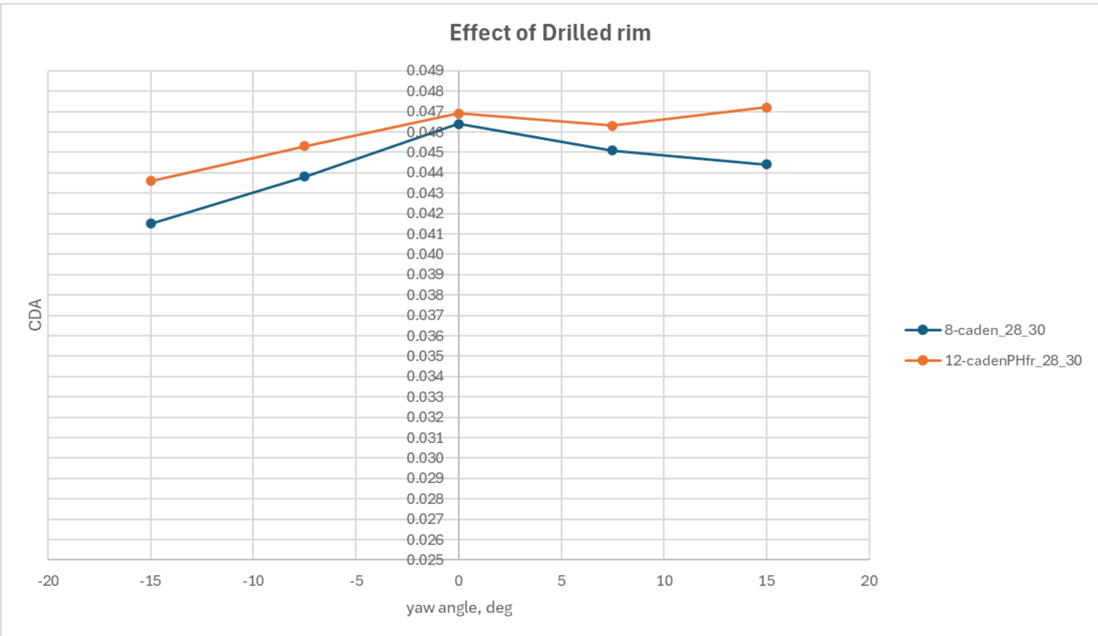


Figure 23 - Drilled rim vs. baseline

Summary

- A range of competitor and feature development tests were performed in a ‘bike&wheels-only’ setup at a constant 50 km/hr speed, across a range of yaw angles. Wheels were rotating @ 29km/hr ground speed.
- The tyre size is seen to be a dominant feature in the aerodynamic performance of the wheels tested.
- Overall, it was seen that having a rim width suited to the tyre is as important as maximising the depth (Scope is 65 vs. Caden 60mm, vs. Reserve front 53mm).
- With the narrower tyres (28 or 111 aero front, 30 rear) the Scope 6A slightly outperforms the Caden.
- With the hidden nipple feature, the Caden has equal performance with the Scope using the 111 Aero tyre.
- With the 30 and 32mm tyres, the Caden outperforms the Scope wheels, which is likely due to its greater external width (something that may be the cause of the slight penalty with the 28mm tyre).
- The Reserve wheels were generally ranked behind the Scope and Caden options in all cases.
- There was no apparent penalty for the Caden going from a 28 to a 30mm tyre on the front.
- All wheels generally had a ~1-1.5 W drag increase going from a 30 to a 32 front tyre.
- In terms of Caden development features, on reviewing the data it was concluded:
    - There was no measurable difference for the carbon spokes
    - Hidden nipples were a small (~0.5W) benefit on the front wheel only
    - Low spoke count with narrower hub flange was a similar (~0.5W) benefit also.
    - The custom drilled rims were a drag penalty vs. the standard rim.

Summary of results at 40 and 50 km/hr:

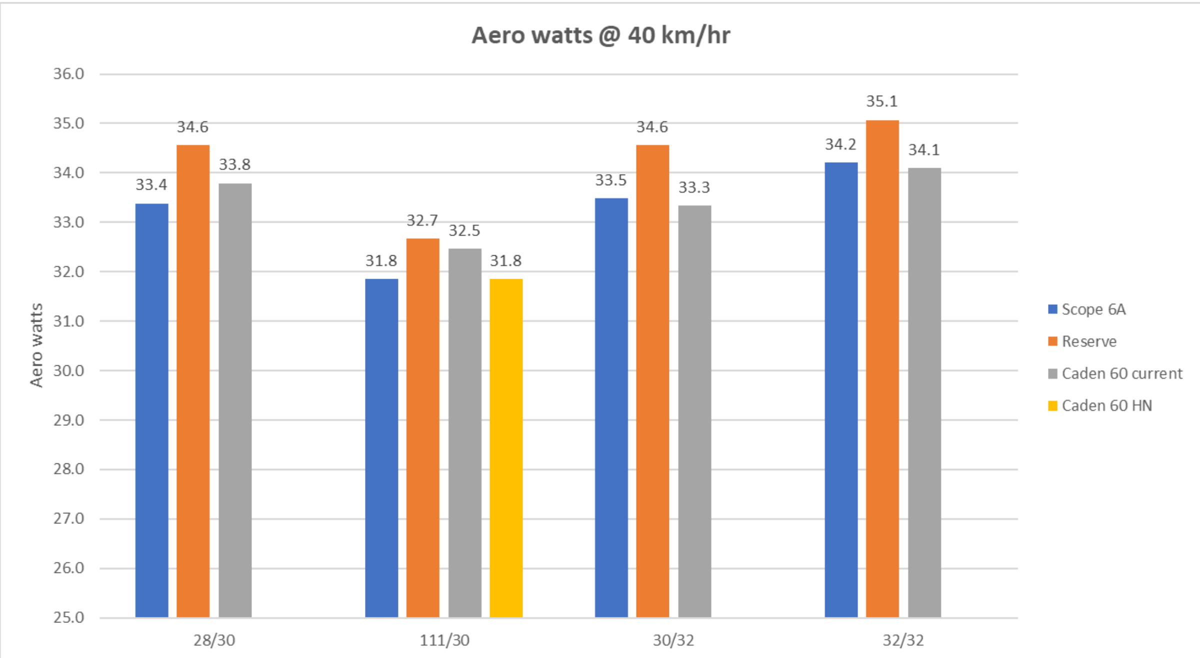


Figure 24

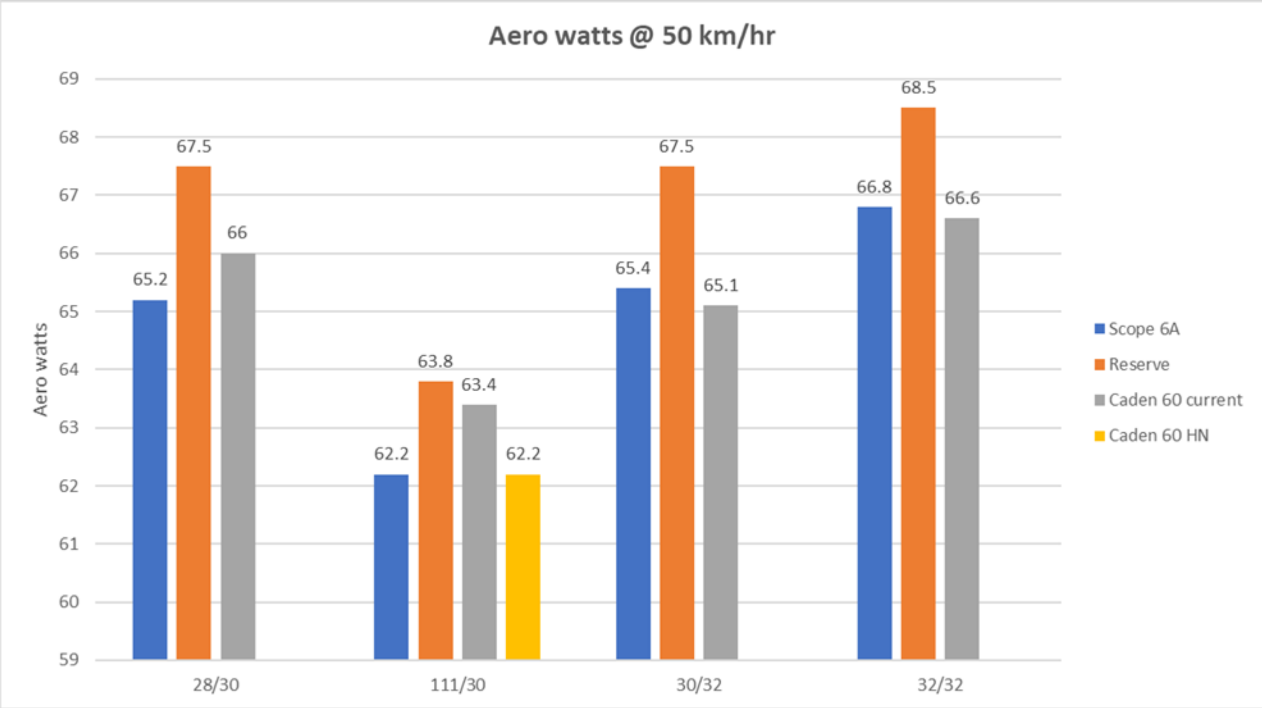


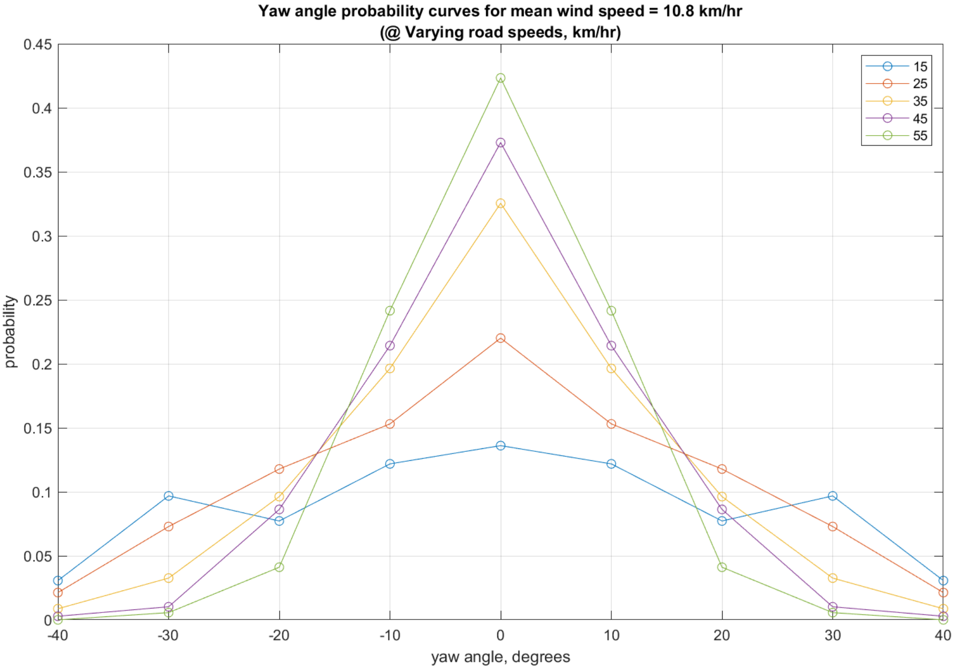
Figure 25

References

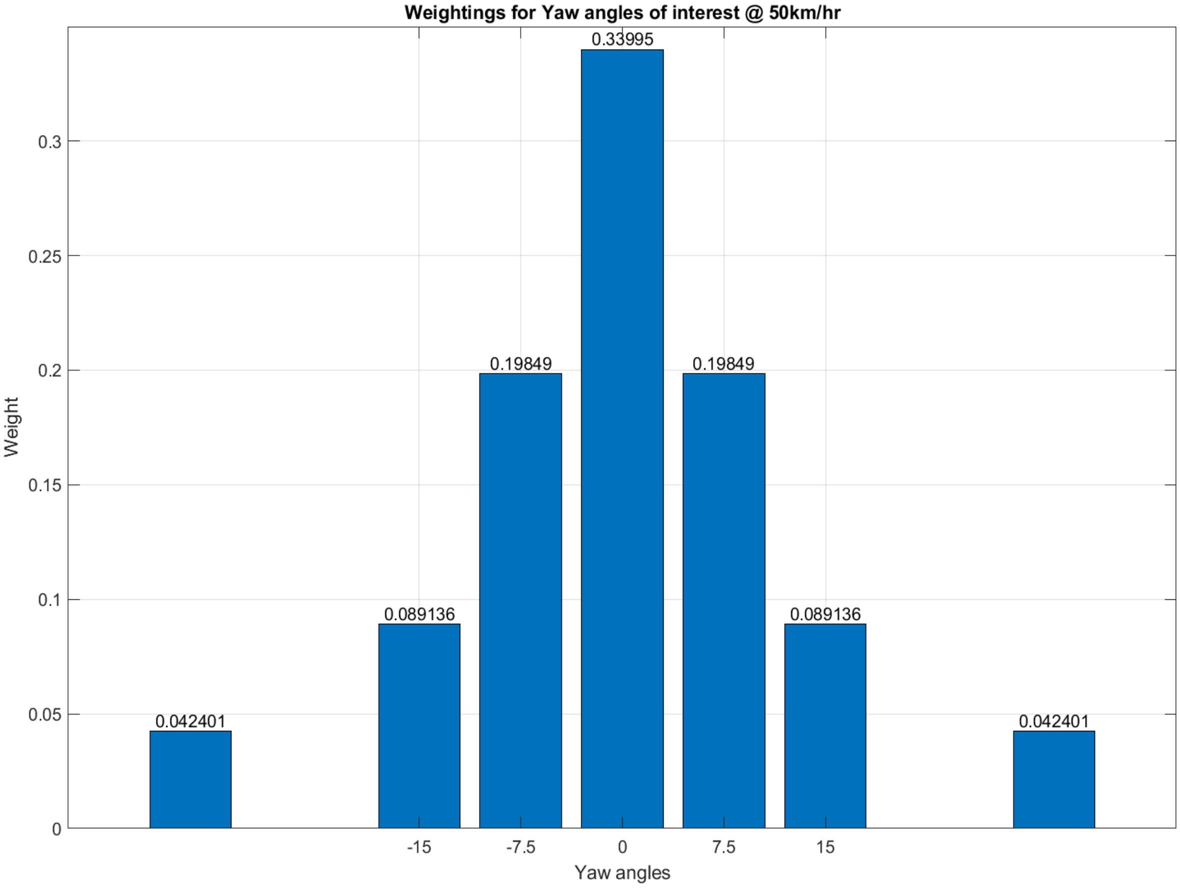
1. Howell, J., Passmore, M., and Windsor, S., "A Drag Coefficient for Test Cycle Application,"
   SAE Technical Paper 2018-01-0742, 2018, doi:10.4271/2018-01-0742.

Appendix A

Wind weighted average function follows the procedure as in reference 1.
Using statistical wind fluctuations about a prescribed mean value, for which the SAE standard value is 10.8 km/hr, a weighting function per measured yaw angle can be calculated for a given vehicle speed.
This helps understand the relative importance of aerodynamic performance at different effective yaw angle ranges.
As shown below, a faster ground speed places more emphasis on low yaw angles and vice-versa. For most practical cycling scenarios of 25km/hr and upwards, focussing the development in the +/- 15 degree range is appropriate.
This approach is also useful when distilling data down to a single metric is required.
However: a robust approach to aerodynamic development is to ensure good aerodynamic performance across the whole yaw range.



The weights used for the data presented in this report are as follows. It can be noted that the weights do not sum to 1. This is due to the residual values greater than 15 degrees not being included.


Weightings for Yaw angles of interest @ 50km/hr
Weight
Yaw angles
0.042401
0.089136
0.19849
0.33995
0.19849
0.089136
0.042401
-15
-7.5
0
7.5
15
0
0.05
0.1
0.15
0.2
0.25
0.3

Appendix B

Repeatability

- In line with standard error analysis, the system error in C_DA, from the inherent sensor accuracy of the wind tunnel components that measure the dynamic pressure and the drag force is:
  - $\frac{d(CDA)}{CDA} = \sqrt{(\frac{d(q)}{q})^2 + (\frac{d(D)}{D})^2}$
  - = 0.21%
- In addition to this, there is the variable run to run error due to object movement. This is specific to the test case and should be accounted for by means of repeated tests of a reference / baseline configuration. From this an appropriate statistical approach such as confidence interval may be calculated to guide results interpretation.

Results excel file (if provided)

- Sheet 1 – front sheet
  - Information on how the file was processed
  - Re char length: Characteristic length used to define the Reynolds number. Typically set to 0.1m for human powered ground sports
  - Aero power rho, velocity: values used to calculate required power to overcome the aerodynamic resistance in the subsequent data sheets
  - Strut tare ON/OFF: Whether a strut tare has been applied to the CDA values in the data.
- Sheet 2 – Data for all runs, points
  - Generally, we group a test configuration into a 'run'
  - Within a 'run' there may be multiple measured points, for example a sweep of speeds and/or yaw angles
  - Here, 'WOZ' stands for 'wind off zero'. This is a control measurement we do periodically to check for drift in the balance.
  - Column headers:
    - Airspeed – m/sec. Multiply by 3.6 to get km/hr.
    - Dynamic pressure, Pa. Wind load (speed and air density).
    - Reynolds number. Non-dimensional. Important parameter particularly when comparing wind-load sensitive aspects.
    - Temp, degC.
    - Yaw angle, deg. Zero = Straight-ahead. Positive = Turntable rotates counter-clockwise (front edge to the left).

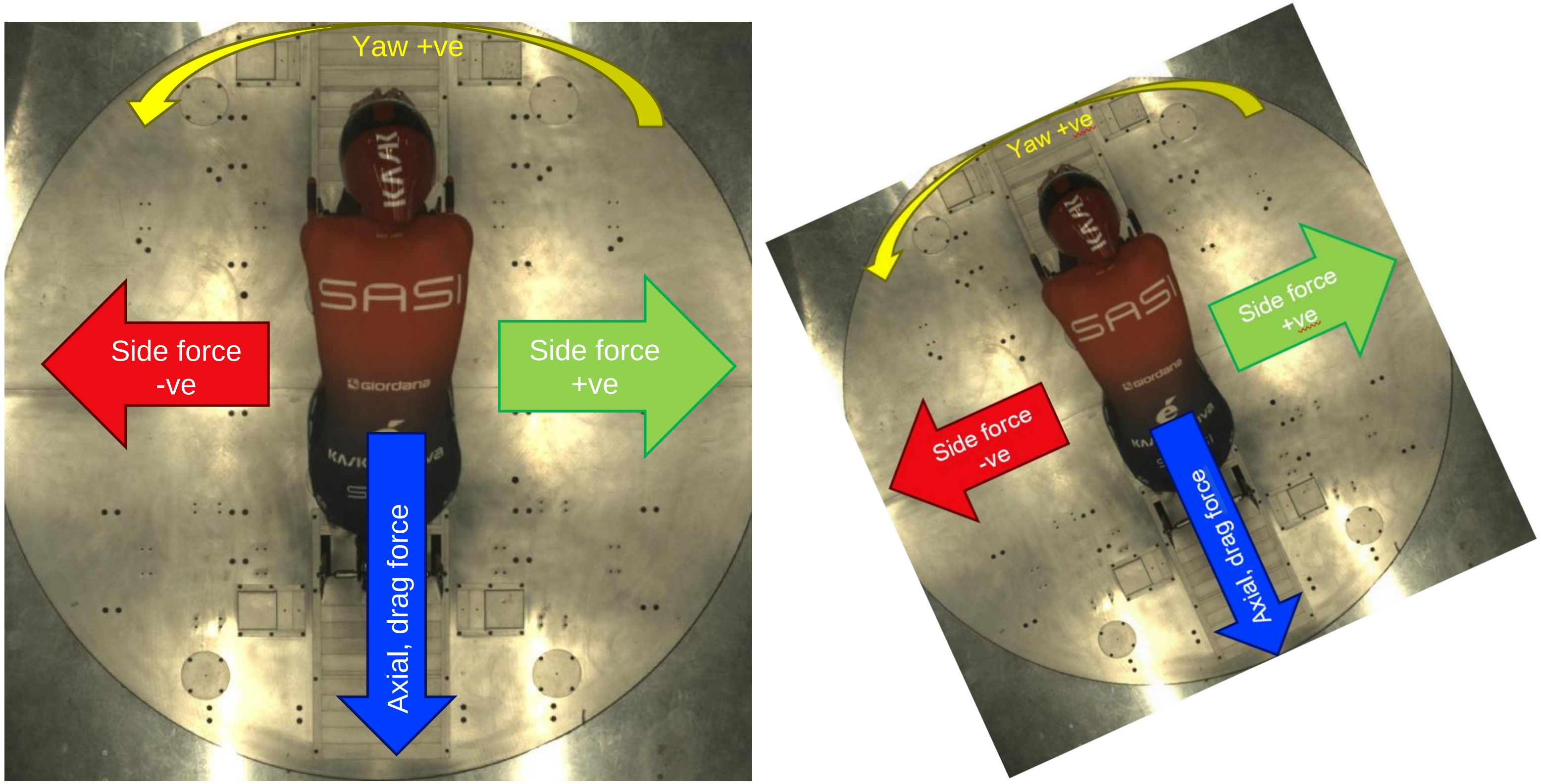
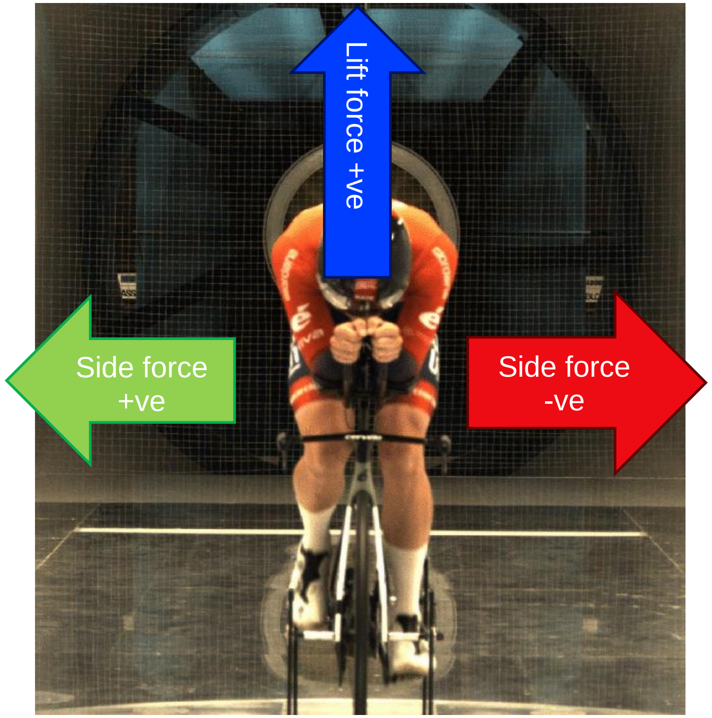


Figure 26 - Horizontal plane force definitions

- Drag force. Total measured X-axis drag force in Newtons.
    - Includes the drag of the struts.
    - ‘Body-axis’: Aligned with the axis of the balance / turntable i.e. when yawed, forces are still aligned with the test object axis, rather than the wind direction.
- CDA. ‘Shape efficiency factor’. Primary parameter of interest in competitive sport. Shows differences in object size and/or how aerodynamically efficient they are.
    - CDA = (Drag force / dynamic pressure)-strut tare

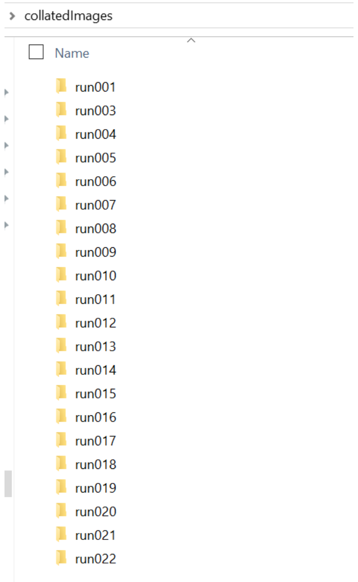
  - Strut tare is test object and yaw angle specific
  - Front sheet will indicate whether this has been applied
- Aero power, Watts: Power required to overcome the aerodynamic drag at a given CDA and wind load
  - Aero power = CDA * Dynamic pressure * Vehicle speed
  - Uses values of air density and speed as defined on front sheet
  - Note this value does not represent the total power output required to travel at that speed. Typically you will need to add power to overcome mechanical friction, rolling resistance, plus any kinetic or potential energy changes.
- CSideA, CLiftA: Side (Y-axis) and Lift (Z-axis) force equivalents of CDA.
  - CSideA = Side force / dynamic pressure
  - CLiftA = Lift force / dynamic pressure
  - No strut tare is applied in any case to these values.
- Side, Lift forces: Lateral and vertical loads measured in Newtons.
  - Positive defined by Right-hand rule with X-axis aligned with the wind direction.
  - Side force – Y-axis: Typically will be positive when object is yawed in the negative direction.
  - Lift force – Z-axis: Positive = vertical upwards.
  - Values in Body axis as per drag
  - No strut tare
- Roll, pitch and yawing moments in Nm
  - Positive defined by Left-hand rule about the X, Y and Z axes respectively.
  - Roll and pitch are about a point 414mm below the turntable centre*.
    - *Ask us if you would like these transformed to an alternative location.



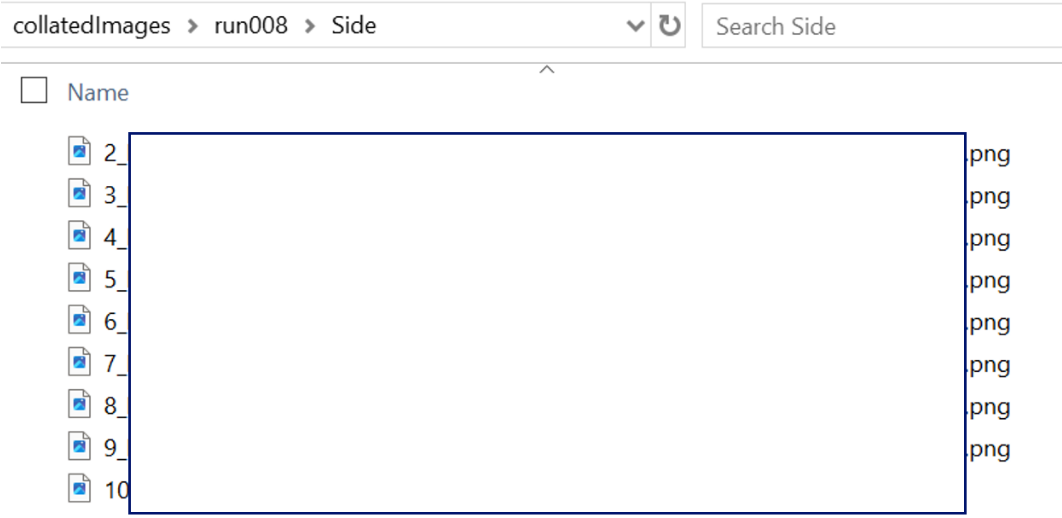
- Sheet 3: Configuration average values.
    - Any repeated yaw or speed data points within a run are averaged.
    - Intended to make comparative plotting of configurations straightforward.

Images (if provided)

- If images have been recorded for your test, you will receive a zipped folder containing a sub-folder for each test ‘run’:



- Within each folder there are ‘Front’, ‘Side’ and ‘Top’ folders that relate to the three cameras capturing images during the testing.
- Each camera folder then contains the <u>first</u> image frame for each test point that was captured for that run.
- These run and point numbers can be cross-referenced with your excel data file to select the one that corresponds to the configuration, yaw angle and test speed you are interested in.



collatedImages > run008 > Side
Search Side
Name
2_ .png
3_ .png
4_ .png
5_ .png
6_ .png
7_ .png
8_ .png
9_ .png
10