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The wind-averaged aerodynamic drag of competitive time trial cycling helmets

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Abstract

This paper documents a wind tunnel test program that measured the aerodynamic drag (F_d), lift (F_l) and side force (F_s) of 12 contemporary time trial (TT) helmets at yaw angles of 0 to 15°. F_d measurements at yaw were subjected to a novel analysis technique adapted from the automotive fuel efficiency literature to provide a single wind averaged drag ($\overline{F_d}$) at a velocity (v) of 14.75 m sec^{-1} (53 km/h). Ranked wind averaged F_d measurements of TT helmets provide a simple performance index and it is recommended that this analytical procedure be adopted by the bike industry to permit uniform F_d comparisons of helmets, wheels, frames and other components that are subjected to yaw angle wind tunnel tests.

Keywords: Time trial helmets; cycling; wind-averaged drag; aerodynamic drag;

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1. Introduction

In cycling, the power required to overcome F_d increases as the cube of v, so the faster a cyclist pedals, the higher the F_d and the greater the power output required by the cyclist. Simply put, to double the speed of a bicycle, power output must be increased eight times. Early in the development of the sport, cyclists recognized that F_d could be reduced by reducing the cyclist's wind facing or projected area normal to the wind (Ap) and by minimizing the drag coefficient (C_d) of the body and the bike through the use of streamlined equipment. Since F_d accounts for up to 90% of the force retarding the forward movement of the rider (rolling resistance and bearing friction accounting for the other 10%) and since a rider is responsible for approximately two thirds of the combined bike+rider drag, reducing the F_d on the rider is of the utmost importance [1]. Differences in the shape and design of time trial (TT) helmets

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can lead to significant differences in F_d so appropriate design of these items is important for optimal race performance.

Several researchers have measured the F_d of TT helmets and have considered the effect of helmet tail height, helmet shape and the presence of a visor on F_d under different yaw angle wind conditions. For example, Blair and Sidelko [2] and Chabroux et al. [3] wind tunnel tested TT helmets with the helmet tail at different heights, relative to the back and determined that, while all TT helmets provide less F_d than a road helmet at a "normal" helmet angle, different helmets will provide the lowest F_d at different helmet tail heights. Blair and Sidelko estimate that the correct use of a TT helmet can reduce cycling power requirements by 10 to 30 watts (2.2 to 6.6% of total cycling power). Chabroux et al. [3] determined that the use of a face shield would reduce F_d by 1.56 to 2.32% at excessively low or high helmet tail heights but not at a "normal" head angle. In addition, Blair and Sidelko [2] found that different helmets provide the lowest F_d at yaw angles of 5, 10 or 15°, so that there is an interaction between helmet shape and F_d at yaw. Chabroux et al. [3] found that the shape and size of front vents on a TT helmet do not affect the F_d of the helmet.

In measuring F_d of bicycle helmets or components the industry standard procedure has been to measure F_d at discrete yaw angles, convert the measured wind axis F_d to bike axis F_d at each yaw angle and to then provide a summary table of the F_d of each helmet over a range of yaw angles. Due to differences in helmet shape, each helmet will suffer stall or increased turbulence at a different yaw angle, so that interpretation of the results is often difficult for both industry technicians and consumers.

In conducting automotive drag studies for improved vehicle fuel efficiency, Cooper [4], [5] and Leuschen and Cooper [6] developed a numerical method to integrate discrete yaw angle F_d measurements of automobiles and heavy trucks into a single "wind averaged" C_d where the average F_d measurement assumes a wind that is equally probable from all directions. The wind averaged C_d assumes reasonable yearly wind statistics, including a mean North America average wind speed of 3.06 m sec^{-1} (11 km/h). The C_d is normalized on road speed, not resultant wind speed, making it simpler to use in numerical simulations. The C_d becomes a function of road speed, since C_d rises at lower road speeds where the wind is an increasing proportion of the resultant wind. The "wind averaged" drag ($\overline{F_d}$) is a useful way to simplify F_d data and allow comparison of the impact of aerodynamic improvements on the fuel economy of transport vehicles.

Cooper [5] also noted that the probability of large yaw angle winds is not fixed so that it is pointless to design vehicles with low F_d characteristics at high yaw angles if those conditions seldom occur on the road. Cooper [7] provided a graph of the probability that a vehicle would exceed a given yaw angle wind for several road speeds and interpolated values from that graph are provided in Table 1 for both powered vehicle (88.5 km/h) and bicycle speeds (48.2 km/h). For powered vehicles, the yaw angle range is reduced at high cruising speeds, with less than a 10% probability of exceeding a yaw angle wind of 10° at a road v of 88.5 km/h. With bicycles, the yaw angle range is somewhat larger, with a 28% chance of exceeding a 10° yaw wind and a 5% chance of exceeding a 20° yaw wind however, there is little point in collecting F_d data at yaw angles exceeding 20° because the probability of encountering these winds on a bicycle is very low.

The current report documents the results of a wind tunnel investigation to measure the F_d and F_l of 12 prototype and commercially available TT helmets where the yaw angle F_d data was analyzed with a modified $\overline{F_d}$ formula and the mean wind speed was estimated to be 3.0 m sec^{-1} (10.62 km/h) at the rider's seat height (Appendix A).

Table 1. Probability of exceedance of various yaw angle winds at two vehicle road velocities (after Cooper [5])

Road Velocity km/h (mph)	0 degrees	2.5 degrees	5 degrees	7.5 degrees	10 degrees	15 degrees	20 degrees
88.5 (55)	1.0	0.61	0.29	0.15	0.08	0.01	-
48.2 (30)	1.0	0.80	0.60	0.43	0.28	0.12	0.05

2. Methods

2.1 Wind tunnel, drag and velocity measurements

All tests were performed at the University of Washington Kirsten Wind Tunnel located in Seattle, Washington, USA. The Kirsten tunnel is a dual fan, closed circuit wind tunnel with a 2.44 x 3.66 x 3.05 m test section and cross-sectional area of 8.75 m^2. Drag measurements on the mannequin and helmet were made with a six component balance programmed to collect F_d measurements at a rate of 10Hz for 15 seconds, yielding 150 samples for a given F_d measurement. These values provided one data point at a particular dynamic pressure (q). The balance has a published resolution of +/- 0.058 N. All data were corrected to model axis values to account for the influence of side force on the measured helmet F_d. The formula required to calculate the model axis drag (D_{bike}) is as follows:

$$D_{bike} = D_{tunnel} \cos\beta - S_{tunnel} \sin\beta \qquad (1)$$

where ß is the yaw angle of the helmet (in degrees); S_{tunnel} is the side force value, measured perpendicular to the tunnel axis and D_{tunnel} is the drag force, measured along the tunnel axis. All helmets were tested in a yaw angle sweep of 0, 5, 10 and 15^0 and then again at 0° and all F_d measurements have been reported with the tare drag of the fixture included. In all tests, one data point was recorded at each of four q that approximated 13.4, 14.3, 15.2, and 16.1 m sec^{-1} while for data analysis purposes, raw velocity data were corrected to precise v under standard atmospheric conditions (pressure = 101.1 kPa; temperature = 15°C).

2.2 Wind tunnel model and description of helmets

All helmets were fixed to an adult medium sized fiberglass mannequin head and torso positioned in a TT cycling position and attached by an aerodynamic strut to the wind tunnel balance. Precise repositioning of the helmet was accomplished with a laser pointer that projected a beam onto the side of the helmet. A pen mark on the helmet was used as the target for the laser beam in all subsequent tests. The front forehead lip of the helmet was always aligned with a mark on the mannequin forehead to standardize the helmet orientation. A ruler was used to confirm the height of the helmet tail in all repeat tests.

Helmets were sourced from bicycle retailers and manufacturer's donations that were provided on the condition of anonymity. To protect proprietary data, the actual identity of the helmets has been masked. Of note, however are helmet #5, which is a 1991 vintage foam helmet with stretch fabric cover and helmet #7, which is a current elite level road racing helmet. Several helmets were tested with and without a face shield. The weight of the helmets was measured with a digital scale and found to range from 245 g (helmet #5) to 485 g (helmet #8).

2.3 Frontal Area

Photographs of seven helmets at 0° yaw were recorded with a 50.8 x 76.2 cm reference area in the photograph and the Ap of each helmet and reference area were then measured with a digital planimeter. The helmet Ap were found to range from 0.039 m^2 (helmet #5) to 0.049 m^2 (helmet #10). The exposed Ap of the mannequin with helmet #6 was 0.137 m^2 or 1.57% of the tunnel cross-sectional area of 8.75 m^2. As helmet #6 had an Ap of 0.041 m^2, the exposed mannequin Ap is 1.329 m^2. As the tunnel blockage to tunnel cross-sectional area ratio did not exceed 2% no blockage correction factor was applied to the data.

3 Results and Discussion

3.1 Data Analysis and Experimental Repeatability

The F_d measurements were affected by helmet repositioning errors, random vortices off the model and stand, the accuracy limit of the balance and small oscillations in wind v during a data collection period. To reduce the measurement variability introduced by these variables, a linear regression equation was fitted to the F_d and q data from each test run. In all the tests reported herein, the R^2 value ranged from 0.8953 to 1.0000 suggesting that no flow transition occurred and indicating consistent helmet positioning and wind v. The linear regression analysis was used to predict the F_d at a v of 14.75 m sec^{-1} with respect to the model axis (only at 0° yaw angle are the wind tunnel and the model axis wind v identical). The interpolated F_d at 14.75 m sec^{-1} for all runs for a particular helmet were utilized to calculate the mean, standard deviation and standard error for the F_d, F_l and F_s measurements. The 95% confidence interval of F_d of a helmet that was removed and replaced (helmet #10; n = 3) was +/- 0.147 N (1.01 %) while the 95% confidence interval of F_d for a helmet that was not removed or repositioned was +/- 0.020 N (0.11 %) (helmet #4b).

3.2 Aerodynamic drag of TT helmets

We found that at a v of 14.75 m sec^{-1}, the range of $\overline{F_d}$ was from 14.592 N (helmet #4) to 15.514 N (helmet #8), a difference of 0.922 N or 6.3% (Table 2). Surprisingly, the bald mannequin head had more drag than when it was covered in most of the helmets. This increase in F_d was probably due to a lack of streamlining over the round head and has been observed previously in proprietary research and by Blair and Sidelko [2]. A test of a "road" helmet (helmet #7) showed that the difference in $\overline{F_d}$ between any of the TT helmets and the road helmet (1.530 to 2.452 N or 9.9 to 16.8%) was far larger than the difference between TT helmets, as modern road helmets are uniformly unaerodynamic. The large area of venting and the angle of the vent entry to the wind is the likely cause of the large F_d noted in road helmets [7].

The $\overline{F_d}$ provides a single drag number based on the weighted probabilities that a rider wearing a TT helmet will encounter particular yaw angle winds with the F_d referenced to road speed rather than resultant bike + wind speed. The $\overline{F_d}$ for each helmet is different than the simple mathematical average of the F_d at the four yaw angles because of the yaw angle weighting and the different reference point for v. While the two rankings of helmets are similar, the F_d values are up to 0.88 N higher for the $\overline{F_d}$ calculation. The reason for the higher $\overline{F_d}$ values is most simply explained in that F_d increases more in a headwind than it decreases in a tailwind. For a consumer or retailer, a hypothetical comparison of the mathematical average of the F_d at four yaw angles of helmets #4b and #10 would lead to the erroneous conclusion that helmet #4b is the lower F_d helmet since it has an average of 0.088 N less drag however this ignores its 0.157 N higher F_d at 5° and 0.275 N higher F_d at 10° and over-emphasizes the 0.834 N lower F_d at 15°. Based on the higher probability of encountering a 5 or 10° yaw angle wind, the $\overline{F_d}$ for helmet #10 is 0.138 N lower than the $\overline{F_d}$ of helmet #4b.

3.3 Effect of face shields and sunglasses on TT helmet drag

An comparison of the $\overline{F_d}$ data revealed that there is no advantage to including a face shield at a normal head angle: helmet #4 without sunglasses or shield had 0.030 N less $\overline{F_d}$ than the same helmet with sunglasses and 0.393 N less $\overline{F_d}$ than the same helmet with a shield. Chabroux et al. [3] determined that the use of a face shield did not reduce F_d at a "normal" head angle but did reduce F_d by 1.56 to 2.32% at excessively low or high helmet tail heights. These findings should be replicated and analyzed to determine the $\overline{F_d}$ of helmets positioned at various tail heights.

3.4 TT helmet shape and lift

In motorsports, rider comfort is often compromised by excessive positive F_l on the head created by wind forces on the helmet. The ideal helmet for motorcycle racing will have a slight negative F_l that gently presses down and holds the helmet onto the rider's head at high v. Lift measurements for TT helmets have not been generally published. As F_l values for each helmet were recorded, the F_l of each helmet at various yaw angles could be compared. In general, these results reveal the following:

- F_l values are only about 20% of the magnitude of F_d values at 0° yaw and approximately 10 – 15% of the magnitude of F_d at a 15° yaw angle;
- the TT helmets generally create a slight negative F_l of up to 0.58 N at yaw angles of 0 and 5° and a slight positive F_l of up to -0.96 N at yaw angles of 10 and 15°, compared to the bare mannequin;
- placing a face shield on helmet #4 reduced the negative F_l of that helmet by up to 0.42 N; and

- the road helmet creates a large negative F_l of from -0.62 N at 0° yaw to -1.41 N at 15° yaw.

Overall, current TT helmets do not appear to create much F_l and there would appear to be little point in designing a TT helmet with a significant F_l characteristic.

Table 2: Wind averaged drag, arithmetically averaged yaw angle drag and yaw angle drag measurements of bicycle helmets at 14.75 m sec-1

Helmet No.	Helmet Features	Wind Averaged Drag (N)	Ranking based on Wind Averaged Drag	Simple Mathematical Average of Yaw Angle Drag (N)	Ranking based on Mathematical Average of Yaw Angle Drag	Drag at 0° yaw (N)	Model Axis Drag at 5° yaw (N)	Model Axis Drag at 10° yaw (N)	Model Axis Drag at 15° yaw (N)
4	No face shield	14.592	1	13.886	1	14.151	14.043	14.092	13.249
6	No face shield	14.612	2	14.014	3	14.092	14.033	14.063	13.867
4a	Sunglasses	14.622	3	14.033	4	14.151	14.053	14.063	13.867
5	1991 vintage TT	14.690	4	13.935	2	14.053	14.131	14.249	13.298
1	-	14.828	5	14.220	7	14.190	14.229	14.318	14.151
10	-	14.847	6	14.239	8	14.131	14.229	14.357	14.239
6a	Face shield	14.945	7	14.210	6	14.278	14.229	14.582	13.749
4b	Face shield	14.985	8	14.151	5	14.190	14.386	14.632	13.406
3	-	14.994	9	14.359	9	14.278	14.367	14.514	14.278
-	Bare mannequin	15.102	10	14.749	12	14.386	14.328	14.524	15.759
2	-	15.161	11	14.435	10	14.612	14.582	14.661	13.886
8	-	15.514	12	14.632	11	15.014	15.014	15.004	13.484
7	Road racing	17.044	13	16.357	13	16.367	16.495	16.328	16.230

3.5 Individual time trial savings from the use of a TT helmet

Basset et al. [8] developed a mathematical model of time savings with reduced F_d that was applied to a hypothetical 70 kg rider with a 9.1 kg bike who rode a level, 40-km TT at an average velocity of 14.75 m sec^{-1} (53.1 km/h) that would require an average of 427 W of power. If the simulated rider switched from a road racing helmet (#7) to the lowest drag TT helmet (#4), the 2.452 N reduction in F_d provided by the TT helmet would provide an 89 second (3.28%) advantage. Within TT helmets, the difference in $\overline{F_d}$ between the lowest (#4) and highest drag (#8) TT helmets (0.922 N) would result in a 33 second (1.23%) advantage. Thus, careful selection of the TT helmet could have a significant impact on race placing.

2. Conclusion

The current research has demonstrated that TT helmets reduce a cyclist's F_d during a high speed bicycle race. Most importantly, the wind averaged drag analysis technique, as introduced here, demonstrates significant potential to permit uniform comparisons of TT helmets, bike wheels, frames and other components that are subjected to yaw angle testing by the bike industry.

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Appendix A. Wind Averaged Drag Calculation

In the current application, the cyclist is assumed to travel at a constant speed of v_C = 14.8 m sec^{-1}, relative to the road. In addition, the wind is assumed to maintain a constant magnitude of v_W = 3.0 m/s relative to ground and is instantaneously directed at an angle of φ relative to v_C (φ = 0 corresponds to a headwind).

By vector addition, the wind velocity magnitude, v, as seen by the cyclist, is

$$v = v_C \sqrt{1 + 2\frac{v_W}{v_C}\cos\phi + \left(\frac{v_W}{v_C}\right)^2} \tag{2}$$

Likewise, the yaw angle of the wind relative to the bike axis, ψ, is given by

$$\tan\psi = \frac{(v_W/v_C)\sin\phi}{1+(v_W/v_C)\cos\phi} \tag{3}$$

To compute the wind-averaged drag, the wind tunnel drag data is first corrected from speed v_C to speed v, as a function of φ, using (A1). Also as a function of φ, the bike-axis yaw angle, ψ, is computed using (3). Finally, the wind-averaged drag, $\overline{F}_d$, is computed by integrating $F_d(\phi)$ with respect to φ, over the range from φ = 0 to φ = 2π, and then dividing the result by the range, 2π

$$\overline{F}_d = \frac{1}{2\pi}\int_0^{2\pi}\left(1 + 2\frac{v_W}{v_C}\cos\phi + \left(\frac{v_W}{v_C}\right)^2\right)F_d(\phi)\,d\phi \tag{4}$$

In the current study, the integral in (*4*) was computed numerically over 5° intervals using a midpoint approximation.