Aerodynamics of Time Trial Bicycle Helmets (P226)

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Topics: Bicycle.

Abstract: During a time-trial (TT) stage on flat track at 50 $Km.h^{-1}$, aerodynamic drag force represents 90% of the power developed by the runner (Belluye and Cid, 2001). Given the drag resistance impact on TT performances, aerodynamics optimization of posture and equipment is thus an essential point (McLean and al. 1994, Martin 1996). The purpose of this study concerns the aerodynamic comparison of six TT helmets which the aim is to minimize the aerodynamic drag. The aerodynamics drag resistances (R_D) of nine professional cyclists using these different TT helmets allow to quantify their aerodynamic performances, the visor and the frontal vents influences according to head and trunk tilts assumed during stages. Experiments were carried out in a wind tunnel at a free-stream velocity of 13.9 $m.s^{-1}$. A 3D motion analysis system SIMI MOTION measured cyclists postural angles (three head and two trunk tilts). Statistical analysis shows that drag resistance and frontal area of a TT posture is significantly lower than the classical road posture (-14.9%). Coefficients of drag in road and TT posture are not significantly different ($p>0.05$). Besides, interaction between the global posture and the helmet inclination is significant ($p<0.05$). In TT posture, drag resistance connected with the natural inclination of the helmet is significantly lower ($p<0.05$) than high (-3.4%) and low inclination (-1.5%). Usual inclination of the helmet provides a drag coefficient reduction of 2.2% compared with the other inclinations (not significantly different together). In high inclination, frontal area is significantly higher (2.4%).Without changing the frontal area, the visor allows a significant reduction of the drag coefficient for low and high inclination (-1.5%), and thus of the drag resistance. This reduction is not significant for the natural inclination. Whatever the helmet orientation, frontal vents have no significant influence on drag coefficient and on frontal area.

Key words: Aerodynamic, drag, helmets, time trial, cycling.

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1- Introduction

During cycling, three external forces are applied to the couple bicycle/cyclist: weight, aerodynamic drag force and contact force between road and wheels. Weigth influence depends mainly on the road slope. If the road is horizontal, weight doesn't reduce the speed. However, contact force and aerodynamic drag force act like speed-reducing factors. Contact force is depending on weight and friction factor between road and wheels. During a TT stage on flat track, at an average speed close to 50 $Km.h^{-1}$, aerodynamic drag force represents 90% of the total power developed by the runner (Belluye *and al.*, 2001). This aerodynamic drag resistance (R_D) is given by the equation below (1).

$$R_D = \frac{1}{2} \cdot \rho \cdot A_P \cdot C_D \cdot V^2 \tag{1}$$

Where R_D is the aerodynamic drag resistance (N), ρ is the air density ($Kg.m^{-3}$), A_p is the projected frontal area of the couple bicycle/cyclist (m^2), C_D is the aerodynamic drag coefficient and V is the air velocity ($m.s^{-1}$). Measurements of drag resistance, projected frontal area and air velocity are discussed in the next section.

Given the drag resistance impact on TT performances, aerodynamics optimization of posture and equipment is thus an essential point. Previous studies (McLean *and al.*, 1994, Martin 1996) defined four postural criteria reducing cyclists drag resistance: back parallel to the ground, elbows closed up, forearms tilted between 5° and 20° with respect to the horizontal, knees closed up to the frame. In order to reduce the drag resistance (R_D) and thus to improve the TT cyclists performances, the purpose of this study concerns the aerodynamic comparison of six TT helmets having different shapes. Indeed, the main aim of the helmets is to protect the head from impacts. Moreover, shape design of TT helmets avoids flow separation occurrences in order to minimize the global cyclist aerodynamic drag. To perform this aerodynamic comparison, a series of tests was carried out in a wind tunnel, on different helmets depending on the postural angles.

The aerodynamics drag resistances (R_D) measured with these different helmet shapes allowed to quantify the external geometry influence, the visor influence and the frontal ventilation influence according to head tilt and global posture (trunk inclination). In addition, measurements of the projected frontal area (A_p) of the couple bicycle/cyclist allowed to work out the aerodynamic drag coefficient (C_D) relative to the use of each helmet.

2- Methods

2.1 Subjects

Nine professional male cyclists (age: 25.0±3.4 years; height: 1.79±0.06 m; weight: 69.3±5.5 kg; mean±σ) volunteered as subjects for this study. Each subject and a sport director of this professional cycling team gave informed consent prior to the tests campaign.

2.2 Equipment

Six different helmets were compared in this study. Three of them were *Louis Garneau Rocket* helmets (1, 4, 5) with the same external geometry (size M) as shown in Figure 1. One of these helmets was equipped with a large visor (4) and another had two large frontal vents (5) as shown in Figure 7. The other helmets were a *Giro Rev 6* helmet (2, Figure 2) and a *LAS Cronometro* helmet (3, Figure 3). In order to assess the performances of these TT helmets, the aerodynamic characteristics of a road cycling helmet (*Louis Garneau Titan Carbon* helmet) (6, Figure 4) were also studied. The bicycles used in these experiments were TT bicycles equipped with rear disc racing wheels and adapted to the cyclists anthropometric characteristics.

Figure 1 - Louis Garneau Rocket (1, 4, 5).

Figure 2 - Giro Rev 6 (2).

Figure 3 - LAS Cronometro (3).

Figure 4 - Louis Garneau Titan Carbon (6).

2.3 Wind tunnel

Experiments were carried out in the test-section of the S1L subsonic wind tunnel (Marseille, France). Characteristics of this wind tunnel are a free-stream velocity up to $V_\infty = 100$ m.s^{-1}, a turbulence intensity lower than 0.3% and a constant temperature within the test-section ($\Delta T<1°C$). During these experiments, the free-stream velocity was fixed at the average speed in TT stages: i.e. 13.9 m.s^{-1}. The velocity in the wind tunnel was mesured and monitored by a Pitot-static tube installed at the upstream entrance to the test-section. Considering the test-section dimensions (octagonal section with inside circle of 3 m in diameter; length: 6 m), no walls boundary layer effects were interfering during measurements.

2.4 Instrumentation

2.4.1 Drag force measurement

In order to determine the drag force of the couple bicycle/cyclist, a cycletrainer was fastened on a drag-mesurement platform mounted in the middle of the test-section. This platform was equipped with ball-bearing slides in the direction of the wind tunnel and with a dynamometer measuring the drag force. The dynamometer voltage was amplified and recorded at 1000 Hz by a computer over a period of five seconds. Data were median filtering (rank: 4; length: 1000 samples) by a LabView program. The accuracy of the drag force measurement is 0.1 Newton. A preliminary measurement allowed to obtain the drag force of the platform equipped with the cycletrainer and therefore to measure the drag force of the couple bicycle/cyclist.

2.4.2 Frontal area measurement

In order to work out the drag coefficient (C_D), the projected frontal area of the couple bicycle/cyclist was measured by a digital camera (frame rate: 250 Hz, resolution: 640 × 480 pixels). Image processing was carried out by computerized planimetry (ImageJ 1.36b) measuring the couple bicycle/cyclist aera in pixels. The camera positioning relative to the reference dimension and the cyclist may be critical for the frontal area measurement (Olds and Olive, 1999). In order to not disturb the upstream flow, the camera was fixed downstream the cyclist, at a distance of 3.5 m from the crankset axis at the height of the saddle. A square reference board (area = 0.42 m^2), placed next to the crankset and perpendicular to the wind tunnel axis, has allowed to calculate a pixel/m^2 conversion ratio. The camera focal length corresponded to the reference board position. A frontal area model, in TT posture, according to the cyclists anthropometric characteristics (Heil 2001), the head tilt and the helmet length will be provided from these measurements.

2.4.3 Postural angles measurement

In order to measure the cyclists postural angles, the 3D motion analysis system SIMI MOTION (SIMI Reality Motion Systems GmbH, Germany) was installed in the test-section of the wind tunnel so as to not disturb flow upstream the couple bicycle/cyclist. This system is composed of three digital cameras (frame rate: 250 Hz, resolution: 640 × 480 pixels) synchronized by the motion analysis software. Head and trunk tilts were measured using two markers on each helmet (positioned horizontally) and two markers on the cyclist (posterior superior iliac spine and acromion).

For each helmet, the cyclists have assumed two trunk inclinations with respect to horizontal (α_1= 34.8°±2.8; α_2= 17.4°±3.4; mean±σ) corresponding to a road posture (hands on handlebar and arms straight) and to a TT posture (hands on aerobars, forearms on armrests and arms bent). For both orientations of the trunk, the cyclists have assumed three head inclinations with respect to horizontal (β_1= -66.4°±4.3; β_2= -36.2°±9.2; β_3= -9.5°±9.1 (for α_1) and β_3= -16.8°±8.7 (for α_2); mean±σ) corresponding to a low, an usual and a high tilt. These six postures allowed to determine the aerodynamical efficiency of the different helmets according to the positions assumed by the cyclists during a TT stage.

2.4.4 Statistical analysis

Standard parametric statistics were used throughout. Repeated-measures analysis of variance was used to test for significant differences between the drag resistance(R_D), the frontal area (A_p) and the drag coefficient (C_D) using each helmet and for each of the six postures (n=9). In the event of a significant *F*-ratio, *post-hoc* analysis was performed using Newman-Keuls *t*-test. An alpha level of 0.05 was adopted for all analyses. All results are reported as mean±σ.

3- Results

3.1 Global posture influence

In order to quantify the drag reduction corresponding to a TT posture (α_2) compared with a road posture (α_1), a first statistical analysis was carried out on the whole configurations. This study shows that the drag reduction of a TT posture is significant (R_D: 37.8±0.5 N vs. 44.5±0.7 N; $p<0.05$) and provides an average gain of 14.95%. This reduction is only due to the significantly lower frontal area in TT posture (A_p: 0.342±0.007 m^2 vs. 0.398±0.006 m^2; $p<0.05$). Indeed, coefficients of drag in road and TT posture are not significantly different ($p>0.05$). One can be note that the interaction between the global posture and the helmet inclination is significant ($p<0.05$) and this is studied in the following section.

3.2 Helmet slope influence

In order to study the influence of the helmet inclination on the aerodynamic performances, a statistical analysis was carried out on the whole TT helmets, for each inclination and according to both global postures (Figure 5).

For the TT posture (α_2), helmet inclination has a significant influence ($p<0.05$) on drag resistance, on drag coefficient and on frontal area. The *post-hoc* comparison shows that drag resistance connected with usual inclination of the head is significantly lower (R_D: 37.2±0.6 N) than the low slope (R_D: 37.8±0.5 N), which is itself significantly lower than the high slope (R_D: 38.5±0.6 N). On one hand, drag coefficient related to the usual tilt of the head is also significantly lower (C_D: 0.91±0.01) than the high (C_D: 0.93±0.01) and the low inclination (C_D: 0.93±0.02). On the other hand, low inclination of the head (β_1) is shown to be the orientation minimizing the frontal area (A_p: 0.339±0.007 m^2), not significantly when compared with usual orientation (A_p: 0.340±0.007 m^2) but significantly in comparison with high inclination (A_p: 0.347±0.007 m^2).

For the road posture (α_1), the orientation of the helmet is also shown to have a significant influence ($p<0.05$) on the drag resistance, on the drag coefficient and on the frontal area. However, unlike for the TT posture, influence between low and usual inclinations of the helmet is not significant ($p>0.05$) on drag resistance, on drag coefficient and on frontal area. However, there is a significant difference of drag resistance ($p<0.05$) between these two orientations (R_D: 43.6±0.7 N; 43.67±0.8 N) and high inclination (R_D: 46.2±0.7 N). Moreover, drag coefficient (C_D: 0.926±0.008; 0.919±0.013) ($p>0.05$) likewise the frontal area (A_p: 0.392±0.007 m^2; 0.395±0.006 m^2) ($p>0.05$) of low and usual inclinations are significantly different in comparison with drag coefficient (C_D: 0.947±0.013) ($p<0.05$) and frontal area (A_p: 0.407±0.006 m^2) ($p<0.05$) of high inclination.

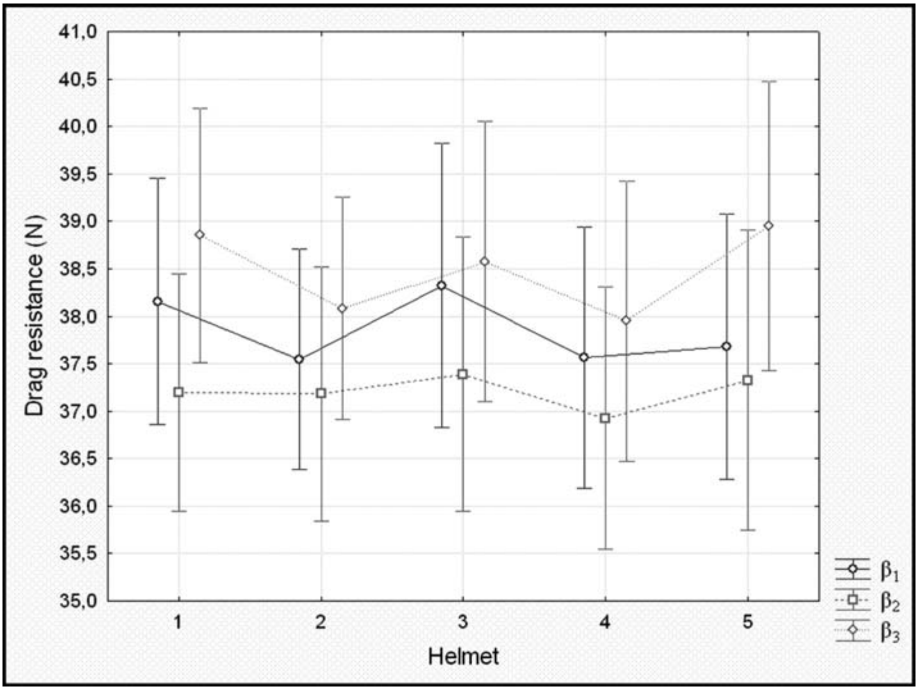

Figure 5 - Helmet orientation influence on drag resistance in TT posture.

3.3 Helmets comparison

In TT posture and for the whole head slopes, helmets drag resistance and drag coefficient are significantly different ($p<0.05$). The most aerodynamic helmet (4) is equipped with a large visor (R_D: 37.5N ±0.6; C_D: 0.92 ±0.01) but it is shown to be not significantly different than helmet 2 (R_D: 37.6N ±0.5; C_D: 0.92 ±0.02). This helmet (2) has great aerodynamic performances due to its frontal surface lower than those of the other helmets (A_p: 0.340m^2 ±0.006). The aerodynamics performances of these two helmets (2, 4) are significantly better than the others tested and allow a mean drag resistance gain of 0.62N (- 1.62%).

TT helmets allow a significantly decrease of drag resistance (mean: -2.4%; max: - 3.5%) when compared to the road helmet (6) (R_D: 38.8N ±0.8). Although it has a frontal surface significantly different only with respect to helmet 2, its drag coefficient is higher than all tested TT helmets (C_D: 0.95 ±0.02).

For only the usual slope of head (β_2), the statistical analysis shows that TT helmets drag resistance and drag coefficient are not significantly different ($p>0.05$). In this posture, helmet 3 has a significantly higher frontal surface (A_p: 0.343m^2 ±0.014) than the other helmets. For this heads slope (β_2), the road helmet (6) has a drag resistance significantly higher (R_D: 38.7N ±0.8) than other TT helmets (mean: +4%; max: +4.8%). Despite the fact that its frontal surface is not significantly different with TT helmets, this drag resistance rise is due to a significantly higher drag coefficient than TT helmets (C_D: 0.95 ±0.02).

3.4 Visor influence

Comparison of helmets 1 and 4 allows to analyze the visor influence on the aerodynamic performances. Indeed, these helmets have the same external geometry but one (4) is equipped with a large visor (height: 80mm). The visor does not change the frontal area. In road posture, statistical analysis shows that the visor has not a significant influence, neither on drag resistance, nor on the drag coefficient. However, in TT posture and for the whole heads slopes, the visor allows a significant decrease of drag coefficient (C_D: 0.93 ±0.02 vs. 0.92 ±0.01) and thus of drag resistance (R_D: 38N ±0.5 vs. 37.5N ±0.6) corresponding to a gain of 1.54%. In addition, the interaction of the visor with the slope of the head is also significant ($p<0.05$) on drag resistance and the drag coefficient (Figure 6). For a high slope of the head (β_3), statistical analysis shows a significant

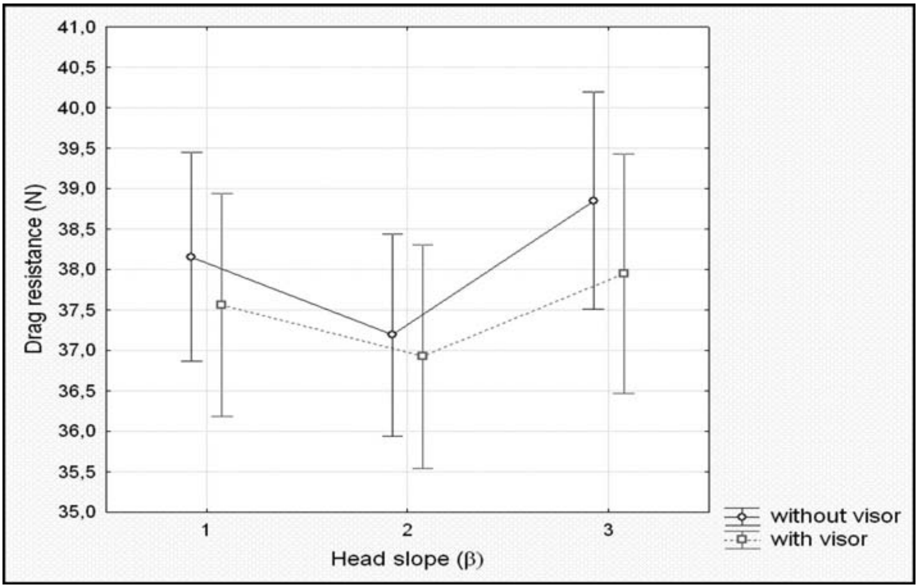

Figure 6 -Visor influence on drag resistance in TT posture.

decrease of drag coefficient (C_D: 0.93 ±0.01 vs. 0.92 ±0.01) and thus of drag resistance (R_D: 38.8N ±0.6 vs. 37.9N ±0.6) corresponding to a gain of 2.32%. For a low slope of the head (β_1), statistical analysis indicates a significant decrease of drag coefficient (C_D: 0.94 ±0.02 vs. 0.93 ±0.01) and thus of drag resistance (R_D: 38.2N ±0.6 vs. 37.6N ±0.6) corresponding to a gain of 1.56%. For a usual slope of the head (β_2), there is no significant reduction of drag resistance and drag coefficient ($p>0.05$).

3.5 Vents influence

Comparison of helmets 1 and 5 allows to study the vents influence on the aerodynamic performances. Indeed, these helmets have the same external geometry but one (1) has four frontal slits shaped vents (two of 5*39mm and two of 5*59mm) and the other presents five vents: two frontal rhombus shaped vents (85*29mm) and three slits shaped vents (5*54mm) on the top of the helmet (Figure 7). These vents do not change the frontal area. Statistical analysis shows that, for the whole slopes of the head, these different vents have not significant influence ($p>0.05$) on frontal area, as well as on drag resistance and drag coefficient.

Figure 7 - Vents on TT helmet.

4- Discussion

Comparison of two global postures conducts to quantify the gain generated by a TT posture with respect to a road posture. The important drag resistance decrease between these postures (-14.9%) is only due to the reduction of cyclists frontal area in the TT posture. Indeed, statistical analysis shows no significant difference on drag coefficient for these postures. Consequently, during a TT stage, cyclists have to keep their TT posture even if they believe to be most powerful when road slope increases.

Comparison between the whole TT helmets and the road helmet (6) shows a drag resistance improvement of 2.4% for the whole heads slopes, and 4% for the usual slope (β_2). Yet, the frontal area of road helmet is not significantly different from TT helmets. Consequently, its drag coefficient is worse than those of TT helmets and decreases its aerodynamic performances. Although classic events speeds are lower than TT speeds, it could be interesting to improve this kind of road helmet drag coefficient.

For the TT posture, statistical analysis shows that helmet inclination has a significant influence on drag resistance. Indeed, usual helmet slope (β_2) provides a drag resistance reduction of 1.72% with respect to a low slope (β_1) and of 3.3% with respect to a high slope (β_3). Actually, the low frontal area increase in usual slope with respect to the low slope (+0.25%) is in agreement with a drag coefficient decreasing of -1.92%. As a result, making frontal area and drag coefficient dot product, a usual helmet slope allows a drag resistance reduction of 0.65N (-1.72%) as shown in Table 1. Consequently, during a TT stage, cyclists have to keep their usual head slope even if they want to relax their cervical muscles.

		Low slope	**High slope**
	R_D	-1.72%	-3.33%
Usual helmet slope	C_D	-1.92%	-1.43%
	A_P	+ 0.2 % (p>0.05)	-1.79%

Table 1 - Helmet slope influence in TT posture.

On one hand, the comparison of TT helmets, for the whole head slopes, shows significant differences on drag resistance and drag coefficient. Aerodynamics performances of helmets 2 and 4 are significantly better than the others tested and allow a mean drag resistance profit of 0.62N (- 1.62%). On the other hand, for usual head slope (β_2), statistical analysis indicates no significant differences on drag resistance and drag coefficient for the whole tested helmets. Moreover, this analysis shows a frontal area significantly larger for helmet 3 with comparison to the other TT helmets. Such a frontal area increase is due to its higher length with respect to the whole TT helmet and does not improve its drag coefficient. Consequently, a higher TT helmet length induces a drag resistance rise. Helmet length could therefore acts like speed-reducing factor.

Comparison of helmets 1 and 4 shows the visor influence in TT posture. For the whole heads slopes, the visor presence produces a significant decrease of drag coefficient and thus of drag resistance corresponding to a gain of 1.54%. This improvement reaches 2.32% for a high head slope (β_3) and 1.56% for a low slope (β_1). However, these aerodynamic performances improvement are no significant for a usual head slope (β_2). As a result, given that cyclists do not preserve their usual head slope along a TT stage, it remains interesting that they use a helmet equipped with a visor.

5- Conclusions

During a TT stage, it has been shown that cyclists have to keep their TT posture, even if they believe to be most powerful when road slope increases. Moreover, they also need to keep their usual head slope, even if they want to relax their cervical muscles. In order to improve their aerodynamic performances, helmets used need to have a large visor in spite of the fact of this one has less impact for a usual head slope. In addition, it seems necessary to limit the TT helmets length and width in order to not increase the frontal area and thus the drag resistance.

6- Outline

In future works and in order to better understand parameters influence on TT helmets aerodynamic performances, it is planned to carry out a PIV analysis (Particle Image Velocimetry) of the downstream flow of the helmet. This detailed flow analysis will provide the characterization of a suited helmet geometry that will improve aerodynamic performances. It is also planned to develop an evolution modelling of the frontal area according to the cyclists posture, their head slope and helmets external geometry.

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