

## Aerodynamic drag in cycling: methods of assessment

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### Abstract

When cycling on level ground at a speed greater than 14 m/s, aerodynamic drag is the most important resistive force. About 90% of the total mechanical power output is necessary to overcome it. Aerodynamic drag is mainly affected by the effective frontal area which is the product of the projected frontal area and the coefficient of drag. The effective frontal area represents the position of the cyclist on the bicycle and the aerodynamics of the cyclist-bicycle system in this position. In order to optimise performance, estimation of these parameters is necessary. The aim of this study is to describe and comment on the methods used during the last 30 years for the evaluation of the effective frontal area and the projected frontal area in cycling, in both laboratory and actual conditions. Most of the field methods are not expensive and can be realised with few materials, providing valid results in comparison with the reference method in aerodynamics, the wind tunnel. Finally, knowledge of these parameters can be useful in practice or to create theoretical models of cycling performance.

**Keywords:** *Aerodynamic drag, coefficient of drag, cycling, projected frontal area, theoretical model*

### Introduction

In cycling, among the total resistive forces on level ground, aerodynamic drag is the main resistance opposed to the motion (Millet & Candau, 2002). At racing speeds greater than 14 m/s, with a classical racing bicycle, aerodynamic drag represents about 90% of the overall resistive forces (Candau et al., 1999; di Prampero, 2000; Martin et al., 2006; Millet & Candau, 2002). Aerodynamic drag is a major concern of cycling research to enhance performance. During a cycling race (e.g. a time-trial), the time difference in performance between elite athletes can be small. The optimisation of aerodynamic drag could be a determinant to enhance the cyclist's performance for the same mechanical power output. In order to minimise this resistance, it is important to know the determinant's parameters, how to evaluate them, and what the evolution of these parameters would be as a function of the position of the cyclist and his or her displacement velocity. The purpose of this review is to present the different field and laboratory methods available for assessment of aerodynamic drag and its most essential parameter, the effective frontal area, in order to enhance cycling performance.

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### Characteristics of the aerodynamic drag

The major performance parameter in cycling is the displacement velocity of both cyclist and bicycle ( $v$ , in m/s). At constant velocity, the ratio of the mechanical power output generated by the cyclist ( $P$ , in W) to the total resistive forces ( $R_T$ , in N) is given by:

$$v = \frac{P}{R_T} \quad (1)$$

By definition, the power output is the quantity of energy output per unit time. At constant speed, the mechanical power output can be assumed to be the sum of the energy used to overcome the total resistive forces (De Groot et al., 1995; di Prampero, 2000). Since aerodynamic drag is about 90% of the total resistive forces at high speed ( $> 14$  m/s), for a constant power output decreasing aerodynamic drag would result in an increase of the velocity of the cyclist-bicycle system. In all forms of human-powered locomotion on land, aerodynamic drag is directly proportional to the combined projected frontal area of the cyclist and bicycle ( $A_p$ , in  $m^2$ ), the drag coefficient ( $C_D$ , dimensionless), air density ( $\rho$ , in  $kg/m^3$ ) and the square of the velocity relative to the fluid ( $v_f$ , in m/s).  $R_D$  can be expressed by (e.g. di Prampero et al., 1979):

$$R_D = 0.5 \cdot A_p C_D \cdot \rho \cdot v_f^2 \quad (2)$$

For a given velocity, aerodynamic drag is dependent on air density and the effective frontal area ( $A_p C_D$ , in  $m^2$ ). Air density is directly proportional to the barometric pressure of the fluid ( $PB$ , in mmHg) and inversely proportional to absolute temperature ( $T$ , in K) (di Prampero, 1986):

$$\rho = \rho_0 \cdot \left(\frac{PB}{760}\right) \cdot \left(\frac{273}{T}\right) \quad (3)$$

Where  $\rho_0 = 1.293 \text{ kg/m}^3$ , the air density at 760 mmHg and 273 K. Air density is also affected by air humidity but this effect is very small and can be neglected (di Prampero, 2000). Moreover, at a given temperature, the barometric pressure of fluid decreases with the altitude above sea level (Table I). At a temperature of 273 K, the decrease in barometric pressure of the fluid with altitude ( $Alt$ , in km) can be described by (di Prampero, 2000):

$$PB = 760 \cdot e^{-0.124 \cdot Alt} \quad (4)$$

As seen in Table I, for the same parameters, the increase of altitude decreases aerodynamic drag by about 24% from 0 m to 2250 m above the sea.

Table I. Effect of air density on aerodynamic drag

Track	$Alt$ (km)	$PB$ (mmHg)	$\rho^a$ ( $kg/m^3$ )	$R_D^b$ (N)
Bordeaux (France)	0	760	1.20	29.8
Colorado Springs (USA)	1.84	605	0.96	23.9
Mexico City (Mexico)	2.25	575	0.91	22.6

$Alt$  = Altitude;  $PB$  = Barometric Pressure;  $\rho$  = Air density;  $R_D$  = Aerodynamic drag;  $A_p$  = Projected frontal area;  $C_D$  = Coefficient of drag;  $v_f$  = Velocity relative to the fluid.; <sup>a</sup>With a temperature equal to 20°C; <sup>b</sup>Based on Equation 2, for a cyclist with  $A_p C_D = 0.221 \text{ m}^2$  and  $v_f = 15 \text{ m/s}$ .

### The projected frontal area

The projected frontal area represents the portion of a body which can be seen by an observer placed exactly in front of that body, i.e. the projected surface normal to the fluid displacement. Some authors assume that the projected frontal area is a constant fraction of the body surface area to establish mathematical descriptions of aerodynamic drag (e.g. Capelli et al., 1993; di Prampero et al., 1979; Olds et al., 1993, 1995). This assumption is helpful since the body surface area ( $A_{BSA}$ , in  $m^2$ ) is easily estimated from the measurement of two anthropometric parameters, body height ( $h_b$ , in cm) and body mass ( $m_b$ , in kg) (Du Bois & Du Bois, 1916; Shuter & Aslani, 2000):

$$A_{BSA} = 0.00949 \cdot h_b^{0.655} \cdot m_b^{0.441} \quad (5)$$

However, Swain et al. (1987) and Garcia-Lopez et al. (2008) have shown that the projected frontal area is not proportional to the body surface area because the  $A_{BSA}/m_b$  ratio tends to be smaller in larger cyclists. Heil (2001) reported that the assumption that the projected frontal area and body surface area are proportional is correct for cyclists with a body mass of between 60 and 80 kg. It is generally considered that the body surface area is proportional to  $m_b^{0.667}$  (Astrand & Rodahl, 1986), whereas the projected frontal area is proportional to  $m_b^{0.762}$  (Heil, 2001). The projected frontal area also can be expressed with the position of the cyclist on the bicycle from the seat tube angle ( $\beta$ , in degree) and the trunk angle ( $\delta$ , in degree) relative to the horizontal (Figure 1). The trunk is represented by the body segment between the hip and shoulder. A goniometer was used to measure the trunk angle:

$$A_p = 0.00433 \cdot \beta^{0.172} \cdot \delta^{0.096} \cdot m_b^{0.762} \quad (6)$$

Nonetheless, Garcia-Lopez et al. (2008) observed a weak correlation between the trunk angle and the projected frontal area ( $r = 0.42$ ,  $p < 0.05$ ). Finally, as logically expected, the results of the different studies show that the projected frontal area is dependent on body height and body mass, position on the bicycle, and equipment used (e.g. helmet, shape of the

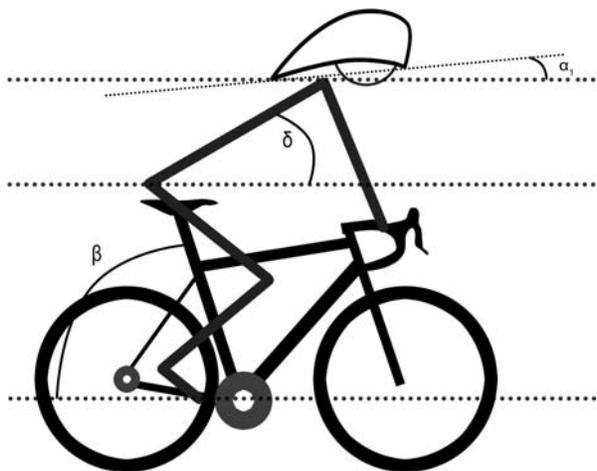


Figure 1. Illustration of the seat tube angle ( $\beta$ , in degree) and the trunk angle ( $\delta$ , in degree) used by Heil (2001) to determine the projected frontal area of a cyclist and bicycle, and the helmet inclination angle ( $\alpha_1$ , in degree) used by Barelle et al. (2010).

frame, clothes). Faria et al. (2005) reported a method to determine the projected frontal area in the aerodynamic position with aero-handlebars using body height and body mass:

$$A_p = 0.0293 \cdot h_b^{0.725} \cdot m_b^{0.425} + 0.0604 \quad (7)$$

Barelle et al. (2010) established two models to determine the projected frontal area in the aerodynamic position with aero-handlebars and a time-trial helmet, as a function of body height, body mass, length of the helmet ( $L$ , in m), and its inclination on the horizontal ( $\alpha_1$ , in degree) (Figure 1):

$$A_p = 0.107 \cdot h_b^{1.6858} + 0.329 \cdot (L \cdot \sin \alpha_1)^2 - 0.137 \cdot (L \cdot \sin \alpha_1) \quad (8)$$

$$A_p = 0.045 \cdot h_b^{1.15} \cdot m_b^{0.2794} + 0.329 \cdot (L \cdot \sin \alpha_1)^2 - 0.137 \cdot (L \cdot \sin \alpha_1) \quad (9)$$

However, the accessibility of direct measurement methods of the projected frontal area, as described further, reduces the interest of such mathematical estimations.

### *The drag coefficient*

The drag coefficient is used to model all the complex factors of shape, position, and air flow conditions relating to the cyclist. The drag coefficient is the ratio between aerodynamic drag and the product of dynamic pressure ( $q$ , in Pa) of moving air stream and the projected frontal area (Pugh, 1971):

$$C_D = \frac{R_D}{qA_p} \quad (10)$$

Where the dynamic pressure is equivalent to the kinetic energy per unit of volume of a moving solid body, and defined by the equation:

$$q = \frac{1}{2} \cdot \rho \cdot v_f^2 \quad (11)$$

The drag coefficient is dependent on the Reynolds number. The Reynolds number is a dimensionless number that gives a measure of the ratio of inertial forces to viscous forces. Thus, the drag coefficient depends on the air velocity and the roughness of the surface. For a given position on the bicycle, the relationship between aerodynamic drag and velocity relative to the fluid is not linear.

In recent wind tunnel investigations, Grappe (2009) showed that the relationship between the effective frontal area and the air velocity was hyperbolic (Figure 2). Measurements were obtained on an elite cyclist with a traditional road bicycle in the traditional aerodynamic position, where the torso is parallel to the ground, with the hands in the drop portion of the handlebars and the elbows flexed at  $90^\circ$ . These data indicated that the effective frontal area decreased between 4.2 and 11.1 m/s and increased between 11.1 and 27.8 m/s. The lowest effective frontal area was found between 11.1 and 13.9 m/s. However, for three cyclists on a track bicycle in the dropped position, where the torso is partially bent over with hands on the drop portion of the handlebars and elbows fully extended, the effective frontal area decreased between 5.6 and 19.4 m/s (Figure 3). The position and the air velocity can have a significant effect on the Reynolds number.

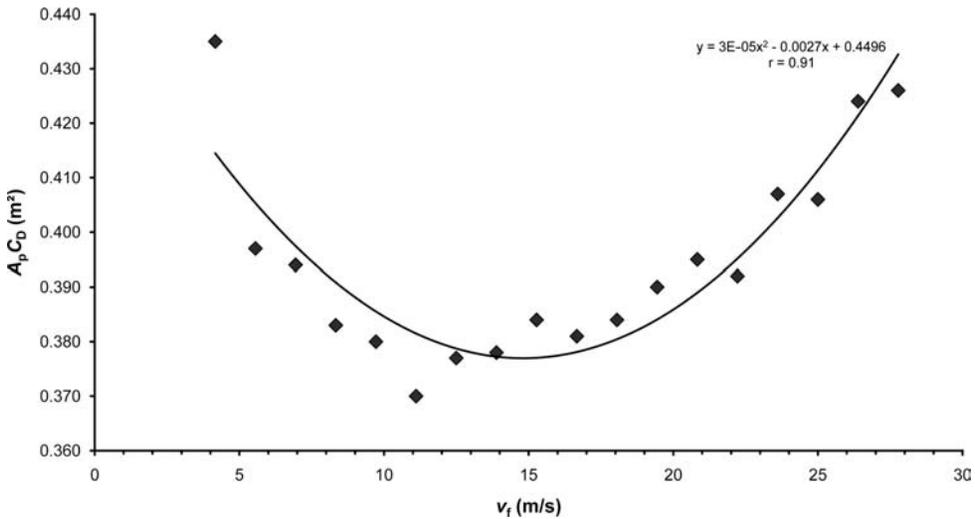


Figure 2. Influence of the air velocity ( $v_f$ , in m/s) on the effective frontal area ( $A_p C_D$ , in  $m^2$ ) for one elite cyclist in static traditional aerodynamic position on a standard road bicycle, in wind tunnel. Data from Grappe (2009).

Oggiano et al. (2009) observed, using a wind tunnel, that aerodynamic drag was also dependent on the velocity and the roughness of the textile worn by the cyclist. Their conclusion highlights the fact that using a rougher fabric can permit an aerodynamic drag reduction at lower displacement speeds, whereas a smoother fabric will perform better at higher speeds.

Grappe (2009) also studied the effect of roughness on the effective frontal area in actual conditions. In a velodrome, the mechanical power generated by a cyclist on a track bicycle was measured with a SRM powermeter (Schoberer Rad Messtechnik Scientific version, Welldorf, Germany) in the traditional aerodynamic position. The power output produced by the cyclist was compared at different velocities between 8.7 and 13.9 m/s in two

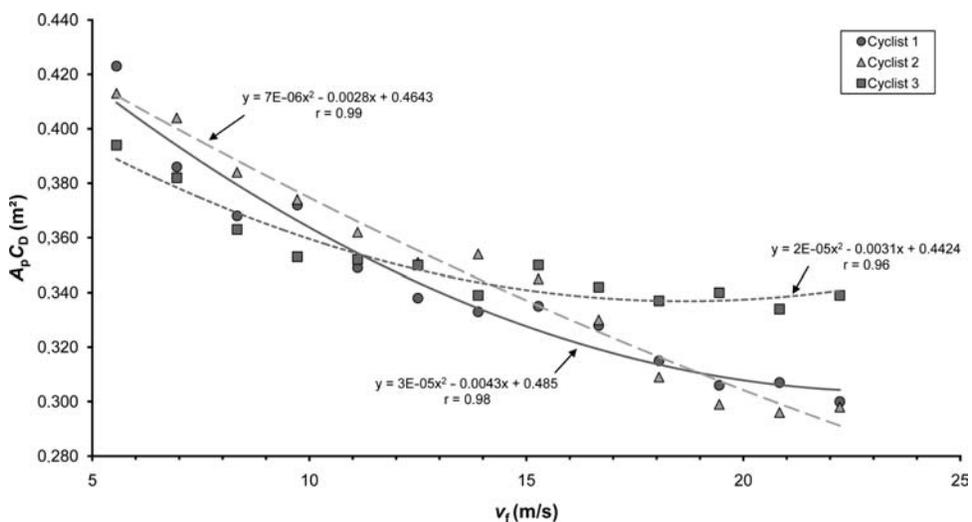


Figure 3. Influence of the air velocity ( $v_f$ , in m/s) on the effective frontal area ( $A_p C_D$ , in  $m^2$ ) for three cyclists in static dropped position on track bicycles, in wind tunnel. Data from Grappe (2009).

conditions: 1) with the cyclist-bicycle system covered with a special 'wax' supposed to improve the roughness and 2) without any treatment (Figure 4). Between 11 and 12 m/s, no difference was shown between the two experimental conditions. Between 8.7 and 11 m/s, the surface treatment allowed an increase in the velocity of the cyclist-bicycle system for the same mechanical power output. However, at velocities of displacement higher than 12 m/s, the velocity did not increase when the 'wax' was used. These results show the complexity of the relationship between the drag coefficient, air velocity, and surface roughness. Heil (2001, 2005) showed that, in cycling, the drag coefficient can be related to the body mass according to data collected in the wind tunnel:

$$C_D = 4.45 \cdot m_b^{-0.45} \quad (12)$$

Heil (2001) noted that the drag coefficient decreases when the body mass increases, e.g. when the body mass increases from 50 to 100 kg, the drag coefficient decreases from 0.76 to 0.56. In view of the findings of Grappe (2009) on roughness and the evolution of the drag coefficient with displacement velocity, these data have to be examined closely. Indeed, a body mass of 100 kg corresponds to a higher body surface area than a body mass of 50 kg, thus resulting in greater skin surface area and a higher drag coefficient. Additional studies are needed to understand the evolution of the drag coefficient as a function of cyclist parameters.

At a given velocity, the effective frontal area is the dominant component of aerodynamic drag. In assessing the effective frontal area, it is possible to evaluate the aerodynamic profile of an athlete and to determine the optimal position on the bicycle for decreasing aerodynamic drag. The measurement or estimation of the effective frontal area allows an evaluation of the aerodynamics of the position and equipment (Faria, 1992), which enables them to be optimised. It is also useful to establish mathematical models to predict performance. Jeukendrup and Martin (2001) used a model with multiple factors concerning the effective frontal area (e.g. body position, bicycle frame and wheels) to show the decrease in the predicted time to assess a 40 km time trial in modifying these factors.

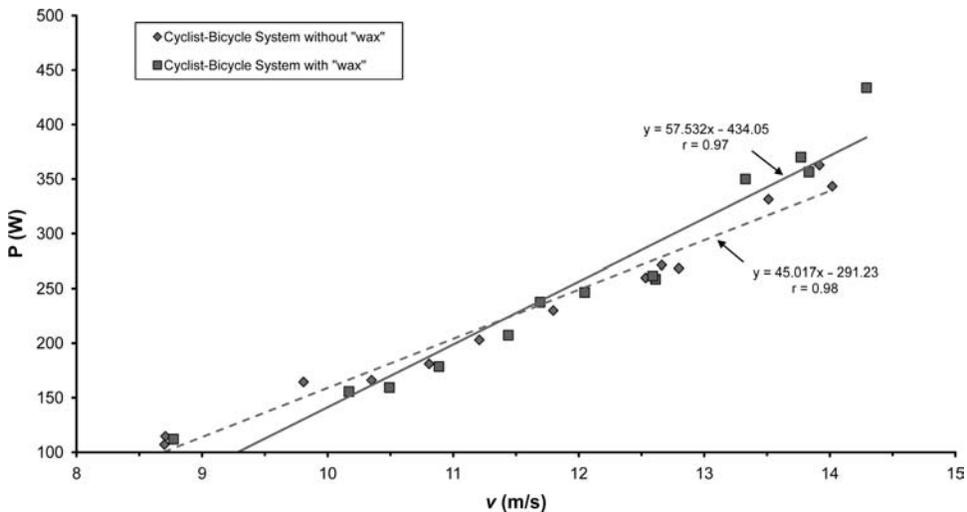


Figure 4. Evolution of the mechanical power output ( $P$ , in W) as a function of the velocity of displacement of the cyclist-bicycle system ( $v$ , in m/s) for a cyclist in a velodrome with a track bicycle in traditional aerodynamic position in two conditions: 1) with the cyclist-bicycle system covered with a special 'wax' supposed to improve the roughness and 2) without any treatment. Data from Grappe (2009).

## Methods of assessment of aerodynamic drag

Different methods are used to evaluate aerodynamic drag under actual conditions or in the laboratory (Garcia-Lopez et al., 2008). Once the aerodynamic drag is known, the effective frontal area can be computed. If the projected frontal area can be directly measured, the drag coefficient can then be determined. Although drag coefficient is the main coefficient in evaluating the aerodynamic profile of an athlete, the validity, sensitivity and reliability of the many methods of effective frontal area and projected frontal area assessment must be discussed. In actual situations, the projected frontal area could help to give indications about a position in a short time with minimal equipment. With the assessment of the effective frontal area, the measurement of the projected frontal area can be a tool to calculate a mean drag coefficient for the most frequently used positions. With this approximation for each position tested, coaches and cyclists could have an aerodynamic profile of a position at low cost.

Results of the determination of projected frontal area and effective frontal area in the literature, using different methods, are presented in Table II. Despite the fact that body mass and height of cyclists affect the measurements, and that position on the bicycle is not always clearly stated, large differences can be observed between methods for a given position. This may be because not all publications clearly describe the position adopted by the cyclists. Also, it is not always clear if the measurements of the projected frontal area take into account the projected frontal area of the bicycle. These methods of assessment are described and discussed in the next sections.

Two ways can be used to determine the effective frontal area. On the one hand, the aerodynamic drag can be directly measured in a wind tunnel. On the other hand, the mechanical power output can be measured by a powermeter (e.g. SRM powermeter Scientific version, Welldorf, Germany) at different speeds and, using Equation 1, the total resistive force to motion is calculated in order to estimate the effective frontal area with respect to air density.

### *Wind tunnel*

Wind tunnels are commonly used to evaluate the effective frontal area. The wind is artificially generated from a fan on the cyclist-bicycle system, and assessment of aerodynamic drag is based on quantification of the ground reaction forces through a plate force measurement (e.g. Davies, 1980; Garcia-Lopez et al., 2008; Martin et al., 1998). In wind tunnel, the cyclist is placed on the bicycle in a test position: i) motionless on a stationary plate force; or ii) pedalling on a treadmill or on a home trainer on a plate force. Before the aerodynamic drag measurement, the force plate must be calibrated and the fan must blow a moderate wind in order to heat the wind tunnel to an optimum temperature. The aerodynamic drag is the parallel force in the same direction as the fluid displacement. It can be evaluated in the wind tunnel and the effective frontal area can be calculated as:

$$A_p C_D = \frac{R_D}{0.5 \cdot \rho \cdot v_f^2} \quad (13)$$

If this method is used in conjunction with an assessment method of the projected frontal area, the value of the drag coefficient can be quantified. The wind tunnel is the reference technique to assess aerodynamic drag because of its validity and reliability (Garcia-Lopez et al., 2008; Hoerner, 1965). This technique is sensitive to wheel type (Tew & Sayers, 1999), yaw angle (i.e. the angle of alignment between the bicycle and the air stream) (Martin et al., 1998),

Table II. Measure of  $A_p$  (m<sup>2</sup>) and estimation of  $A_p C_D$  (m<sup>2</sup>) in different positions with different methods. ( $M \pm SD$ ).

Study	Methods	Subjects			Positions				
		n	Body height (m)	Body mass (kg)	UP (m <sup>2</sup> )	DP (m <sup>2</sup> )	AeroP (m <sup>2</sup> )	BHP (m <sup>2</sup> )	TAP (m <sup>2</sup> )
<b>Measure of <math>A_p</math></b>									
Olds & Olive (1999)	Weighing Photographs	17	1.76 ± 0.08	68.3 ± 9.2	0.605 ± 0.069	0.563 ± 0.071	0.493 ± 0.057	0.364 ± 0.012	
Garcia-Lopez et al. (2008)		5	1.79 ± 0.03	71.6 ± 2.7			0.301 <sup>a</sup> ± 0.011		
Padilla et al. (2000)		1	1.88	81.0			0.375		
Davies (1980)	Digitalization	15	1.77 ± 0.08	69.0 ± 5.9	0.50 <sup>b</sup>				
Capelli et al. (1998)		10	1.81 ± 0.09	70.5 ± 6.0	0.42 ± 0.028 <sup>b</sup>				
Capelli et al. (1993)		2	1.85 ± 0.01	73.0 ± 2.8	0.394 <sup>b</sup>				
Heil (2002)		21	1.82 ± 0.06	74.4 ± 7.2	0.525 ± 0.01	0.531 ± 0.008			0.46 ± 0.0091
Dorel et al. (2005)		10	1.81 ± 0.04	83.0 ± 5.0		0.531 ± 0.014			
Debraux et al. (2009)	Planimetry	9	1.77 ± 0.03	70.5 ± 5.4	0.533 ± 0.031				0.426 ± 0.031
de Groot et al. (1995)		7			0.39 ± 0.028 <sup>b</sup>				
Debraux et al. (2009)		CAD	9	1.77 ± 0.03	70.5 ± 5.4	0.565 ± 0.037			
<b>Estimation of <math>A_p C_D</math></b>									
Martin et al. (1998)	Wind Tunnel	6	1.77 ± 0.05	71.9 ± 6.3			0.269 ± 0.006	0.481 ± 0.017	
Garcia-Lopez et al. (2008)		5	1.79 ± 0.03	71.6 ± 2.7			0.297 ± 0.013		
Padilla et al. (2000)		1	1.88	81.0			0.244		
Defraeye et al. (2010)	Linear Regression Analysis	1	1.83	72	0.270	0.243	0.211		
Davies (1980)		15	1.77 ± 0.08	69.0 ± 5.9	0.280 <sup>b</sup>				
Martin et al. (2006)		1	1.83	96.0					0.332
		2	1.73 ± 0.12	77.5 ± 13.4			0.2 ± 0.021		

Table II – *continued*

Study	Methods	Subjects			Positions				
		n	Body height (m)	Body mass (kg)	UP (m <sup>2</sup> )	DP (m <sup>2</sup> )	AeroP (m <sup>2</sup> )	BHP (m <sup>2</sup> )	TAP (m <sup>2</sup> )
Debraux et al. (2009)		7	1.77 ± 0.03	70.5 ± 5.4				0.361 <sup>c</sup> ± 0.021	
Grappe et al. (1997)		1	1.75	67.0	0.299	0.276	0.262 0.216 <sup>d</sup>		
Capelli et al. (1993)	Towing	2	1.85 ± 0.01	73.0 ± 2.8	0.255 <sup>a</sup>				
di Prampero et al. (1979)		2	1.75	63.0		0.318			
Candau et al. (1999)	Simple Deceleration	1	1.72	66.2	0.355		0.262-0.304		

$A_p$  = Projected frontal area (m<sup>2</sup>);  $A_p C_D$  = Effective frontal area (m<sup>2</sup>); UP = Upright Position; DP = Dropped Position; AeroP = Aerodynamic Position with aero-handlebars; BHP = Brake Hoods Position; TAP = Traditional Aerodynamic Position; <sup>a</sup> Without helmet; <sup>b</sup> Position unclear; <sup>c</sup> In mountain bike; <sup>d</sup> Obree's Position.

and cyclist position (Garcia-Lopez et al., 2002, 2008). The results can be dependent on whether the cyclist is motionless or moving. Indeed, during the pedalling exercise the cyclist significantly increases the aerodynamics. Accordingly, the plate force records the generated forces during pedalling. To obtain a valid measurement of the drag forces, a first step could be to record the forces while pedalling in order to subtract these from the forces measured in a wind tunnel.

Although the wind tunnel technique is still a reference method, it is very expensive (between 5,000 and 10,000 euros per day) and few studies have been published on the assessment of aerodynamic drag using wind tunnels. Furthermore, wind tunnel measurements have some limitations. Candau et al. (1999) explain that testing conditions present limitations: i) if the tested body does not move, the air flow around the bicycle is modified by the floor; ii) if the wheels of the bicycle are stationary, the effect of wind is not measured; and, iii) the cyclist's position on the bicycle during the tests is not necessarily identical to the position in actual conditions. Slight lateral movements that can occur in actual conditions are not present in the wind tunnel. When the cyclist rides on a motor-driven treadmill or a home trainer, limitations ii and iii are resolved, but another limitations appears: iv) the pedalling motion introduces noises in the force measurement system such that there are changes in the forces applied to the treadmill within each pedal revolution; and, v) slight lateral movements (e.g. shoulders) are dependent of the intensity of pedalling.

Few studies have simulated actual conditions of pedalling in a wind tunnel. In Davies' study (1980), the cyclists were instructed to pedal on a motor-driven treadmill at a set speed of 4.7 m/s against wind velocities varying from 1.5-18.5 m/s. To be closer to riding conditions, Martin et al. (1998) simulated pedalling at 90 rotations per minute (rpm), but without resistance, and the front wheel was rotated by a small electric motor. Garcial-Lopez et al. (2002, 2008) tested five different positions to measure the aerodynamic drag of professional cyclists in a wind tunnel using two bicycles, a special time-trial bike with aero-handlebars and a standard bike with standard handlebars. These tests occurred with and without pedalling against a resistance ergometer.

In order to model actual conditions more closely, it could be more practical to use a field method to assess the effective frontal area. This permits lower cost testing in actual conditions and enables selection of the most appropriate position and equipment.

#### *Method of linear regression analysis*

When cycling on level ground at constant velocity, the total resistive forces are mainly composed of two forces, aerodynamic drag and rolling resistance ( $R_R$ , in N). Thus, the total resistive forces can be described by Equation 14 (Capelli et al., 1993; Davies, 1980; di Prampero et al., 1979; Grappe et al., 1997, 1999):

$$R_T = R_D + R_R \quad (14)$$

With

$$R_R = C_R \cdot M \cdot g \quad (15)$$

Rolling resistance represents the contact forces between the ground and the pneumatics of the wheels, and the frictional losses at the bearing and transmission chain (Grappe et al., 1997; Millet & Candau, 2002). Rolling resistance depends on the rolling coefficient ( $C_R$ , dimensionless), the mass of the cyclist-bicycle system ( $M$ , in kg) and the gravity acceleration

( $g = 9.81 \text{ m/s}^2$ ). According to Equations 2, 14 and 15:

$$R_T = 0.5 \cdot \rho A_p C_D \cdot v_f^2 + C_R \cdot M \cdot g \tag{16}$$

The total resistive forces can be determined by measuring mechanical power output as a function of velocity (Grappe et al., 1997):

$$R_T = \frac{P}{v} \tag{17}$$

This method consists of measuring mechanical power output using a powermeter (e.g. SRM powermeter Scientific version, Welldorf, Germany) at different velocity to determine the total resistive forces. To do this, the cyclist performs several trials at different velocities in a selected posture. According to Equation 16:

$$a = 0.5 \cdot \rho \cdot A_p C_D \tag{18}$$

$$b = C_R \cdot M \cdot g \tag{19}$$

Thus

$$R_T = av^2 + b \tag{20}$$

Based on Equation 20, the total resistive forces vary in a linear way with the square of the velocity (Figure 5).

With a linear regression analysis, it is possible to determine the effective frontal area value for the selected posture according to Equation 18 ( $A_p C_D = a/0.5\rho$ ) from the slope  $a$  of Equation 20. If this method is used with a method of determination of the projected frontal area, the value of the drag coefficient can be quantified (Capelli et al., 1998). However, the relationship between the total resistive forces and  $v^2$  is not necessarily linear (Grappe, 2009).

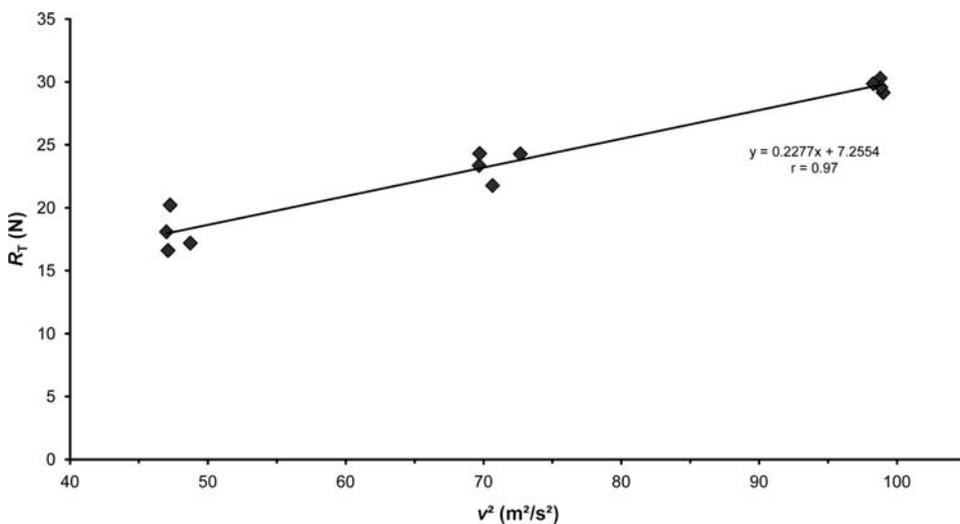


Figure 5. Illustration of the evolution of the total resistive forces ( $R_T$ , in N) as a function of the squared displacement velocity of the cyclist-bicycle system ( $v^2$ , in  $\text{m}^2/\text{s}^2$ ) on level ground with a mountain bike.

The reliability of this method is good (Coefficient of variation (CV) = 3.2%) (Grappe et al., 1997). Grappe et al. (1997) did not observe a significant difference, using the Max One powermeter (Look SA, France), between the aerodynamic position with aero-handlebars, where the lower arms are on the aerodynamic handlebars, and the dropped position. The difference in the effective frontal area between the two positions was 4.6%, and the authors concluded that this method reaches the limit of the sensitivity of the measurement. The powermeter used (Max One, Look SA, Nevers, France) to measure the mechanical power output has a weak sampling frequency (i.e. 4 data per 1 rpm) and the tests were performed in an outdoor velodrome. The use of a more accurate powermeter like the SRM, which has a higher sampling frequency, could lead to a more sensitive measure in the field. It could be helpful in discriminating different positions or levels of roughness.

To verify whether the SRM system could provide a valid measure of cycling power, Martin et al. (1998) compared the SRM measured power with that from the Monark cycle ergometer (Model 818). The statistically valid results indicate that the power measured by the SRM was significantly different ( $p < 0.01$ ) than the power delivered to the Monark ergometer flywheel; the difference was 2.35%. It appears that this difference is characteristic of power loss in chain drive systems (Martin et al., 1998). These authors assume that the SRM provides a valid and accurate measure of cycling power compared with the Monark cycle ergometer.

#### *Measurement of the tractional resistance (dynamometric method): the 'towing' method*

With this method, tractional resistance is determined by towing a subject with a vehicle (e.g. car, motorcycle) by means of a cable (e.g. a nylon cable of 0.003 m of diameter) on a flat track at constant speed. The length of the cable (e.g. 10 m, 25 m) was chosen to minimise the air turbulence caused by the moving vehicle (di Prampero et al., 1979; Capelli et al., 1993). However, air turbulence set up by the towing vehicle and alterations in atmospheric conditions can affect the results (Candau et al., 1999; Garcia-Lopez et al., 2008). During the test, the cyclist's selected posture does not change while being towed by the vehicle. The cyclist can pedal at a selected cadence without a transmission chain to reproduce the air turbulence induced by moving legs during actual cycling (Capelli et al., 1993).

The total resistive forces to the motion were measured with a dynamometric technique from a load cell mounted in series on the cable. The total resistive forces were assessed over several trials at different velocities to obtain a  $R_T$ - $v$  relationship. As for the method of linear regression analysis, the curve of the total resistive forces in function of the square of the velocity has to be plotted, based on Equation 20. With a linear regression analysis, it is possible to determine the effective frontal area value for the studied position according to Equation 16 ( $A_p C_D = a/0.5\rho$ ) from the slope  $a$  of Equation 20. Capelli et al. (1993) tested the repeatability of the towing method by measuring the total resistive forces twice each at six speeds. They found no significant difference between the paired sets of data ( $p > 0.10$ ). The fact that this method cannot be used routinely is an important limitation.

#### *The coasting-down and deceleration methods*

These methods of measuring aerodynamic drag are based on Newton's second law ( $\Sigma F = m \cdot a$ ), where the sum of the resistive forces ( $F$ ) is equal to the product of mass ( $m$ ) with acceleration ( $a$ ). The tests performed in descent (coasting-down method) measure the acceleration of the cyclist in free-wheel and those performed on flat terrain (outdoor and indoor) measure the cyclist's deceleration, also in free-wheel. In a specified position  $i$  in a

descent (Gross et al., 1983; Kyle & Burke, 1984; Nevill et al., 2006) or ii) on flat ground, in a field, or in hallways (Candau et al., 1999) the cyclists brought the bicycle to a defined velocity before they stopped pedalling. The riding position was unchanged and, to reproduce actual conditions with turbulence induced by movement of the lower limbs, the cyclists can pedal without transmission of force to the rear wheel during coasting trials (Gross et al., 1983; Kyle & Burke, 1984; Candau et al., 1999). In this way, the cyclists slowed down due to the air friction and rolling resistive forces over several timing switches.

For the coasting-down method (Gross et al., 1983; Kyle & Burke, 1984), there are six timing switches. The distance between switches is 6 metres and the time is recorded using a chronometer system (to 1/1,000 s). The mean velocity between each switch is calculated to assess linear regression of mean velocity as a function of the distance. The slope of the linear regression multiplied by the mean velocity of the third interval determines the mean acceleration of the bicycle-cyclist system. The total resistive forces are the product of the mass and the acceleration of this system. The aerodynamic drag and the rolling resistance are calculated from the relation between the total resistive forces and the square velocity as shown in Equation 16.

As the coasting-down method is a field method, climatic conditions and the nature of the ground can potentially induce some errors. Kyle and Burke (1984) reported measured variations of nearly 10%. To avoid such errors, the method can be used in hallways (De Groot et al., 1995). De Groot et al. (1995) have developed a small infrared light emitter and detector mounted on the front fork of the bicycle. This system can measure velocity as a function of time during the deceleration phase but there is no information concerning the reliability and sensitivity of this approach.

For the deceleration method (Candau et al., 1999), three switches are disposed in a hallway. The distance between the first and the second switch is 3 metres and the distance between the second and third switch is 20 metres (Figure 6).

The time is recorded using a chronometer system (accurate to 30  $\mu$ s). The total resistive forces were assessed with several trials ( $\approx 20$ ) at different velocities by iterations with a mathematical model describing the deceleration of the trajectory of the cyclist-bicycle system (Candau et al., 1999). The reliability (CV = 0.6%), sensitivity and validity of this method of measuring the effective frontal area (in comparison with the wind tunnel) are excellent. Although this method permits measurement of the rolling resistance of the tyres according to a specific ground surface, it is limited by the significant number of trials needed to determine an evaluation of the effective frontal area.

Of these four methods of assessment of the effective frontal area, the wind tunnel method and the method of linear regression analysis are the most sensitive and reliable. The method

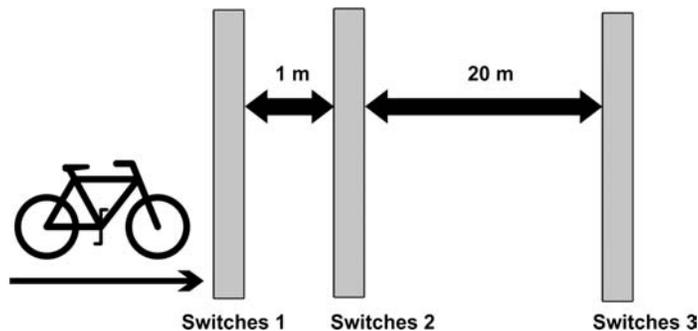


Figure 6. Schematic view of the measurement system for the deceleration method in a hallway and the placement of the three switches.

of linear regression analysis with the use of a powermeter such as SRM provides measurement of the resistive forces in actual conditions. It could also help to discriminate between the effective frontal area values at different positions. However, the wind tunnel allows more accurate and reliable measurements of aerodynamic drag, resulting in a higher sensitivity to small adjustments of the cyclist's position (Defraeye et al., 2010) or equipment (e.g. the helmet) (Barelle et al., 2010). Nevertheless, this method is very expensive. Most coaches and sport scientists have easier access to a powermeter system like the SRM or PowerTap models. The field method could serve to prepare and/or optimise and/or verify wind tunnel results. Finally, Defraeye et al. (2010) showed that computational fluid dynamics provided measurements of drag in good agreement with those obtained by wind tunnel tests. Computational fluid dynamics could be a valuable numerical alternative for evaluating the drag of different cyclist positions with high sensitivity. The advantage of this method is that it allows more detailed insight into the flow field around the body of the cyclist.

Although the effective frontal area is the main parameter in aerodynamic evaluation, it can be highly influenced by the projected frontal area. For a constant drag coefficient, the effective frontal area is proportionally affected by the change of projected frontal area. Moreover, a decrease in the projected frontal area would result in a decrease in the effective frontal area (Defraeye et al., 2010). Two different methods are used to measure the projected frontal area: i) with a calibration frame of known area, such as the method of weighing photographs (e.g. Capelli et al., 1993, 1998; Debraux et al., 2009; di Prampero et al., 1979; Heil, 2001; Olds et al., 1993, 1995; Padilla et al., 2000; Pugh, 1970, 1971; Swain et al., 1987), the method of digitalisation (Barelle et al., 2010; Debraux et al., 2009; Dorel et al., 2005; Heil, 2001, 2002); and ii) without calibration frame, such as planimetry (Olds & Olive, 1999), digital methods using computer-aided design (CAD) software (Debraux et al., 2009)).

#### *The method of weighing photographs*

This method consists of taking a photograph in a frontal plane of the cyclist and bicycle (Figure 7A). A calibration frame with a known area located midway between the subject's hip and shoulders and facing the camera is also photographed. The photograph is printed and the cyclist and calibration frame are cut from the photograph. These separate pieces are weighed using an accurate balance with a high sensitivity ( $\pm 0.001$  g). The actual projected

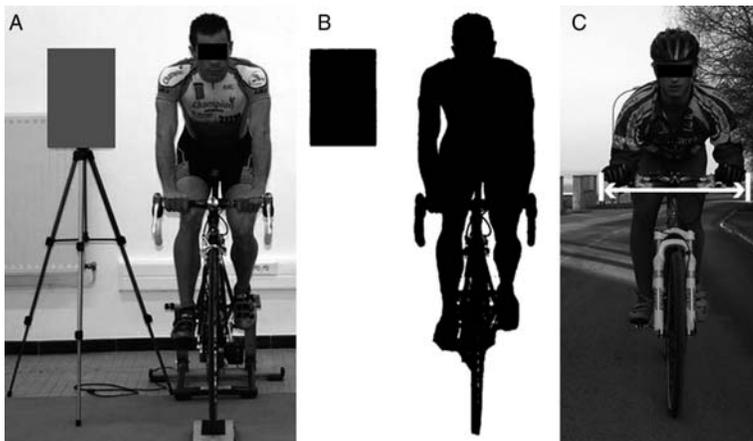


Figure 7. Example of photographs of cyclists used to measure  $A_p$  with different methods: method of weighing photographs (A), method of digitalisation (B), and computer-aided design method (C).

frontal area in square metres is calculated for each image by multiplying the known area of the calibration frame by the ratio of the projected frontal area image weight over the calibration frame image weight (Capelli et al., 1998; Debraux et al., 2009; Heil, 2001; Olds et al., 1995; Padilla et al., 2000).

The method of weighing photographs requires only a calibration frame, a digital camera, a balance with high sensitivity, and a cutting instrument, but it cannot be used in actual conditions because of the need of the calibration frame. Although this method has been used for a long time (Pugh, 1970, 1971; Swain et al., 1987), it is very reliable ( $CV = 1.3\%$ ) (Debraux et al., 2009) and has been used to test the validity of new methods of assessment of the projected frontal area (e.g. Debraux et al., 2009; Heil, 2001).

The method of weighing photographs presents some inconvenience which can be resolved. The cutting of the printed photograph following the outline of the cyclist has to be very accurate, and this operation takes at least 5–6 minutes. Moreover, for the classical format of digital photographs, it is easier to measure only the projected frontal area of the cyclist without the bicycle, unless the photographs are enlarged. To be sure that colour did not influence the mass of photographs, Debraux et al. (2009) weighed five photographs with five different colours. They concluded that colour did not influence the results in this method.

### *Planimetry*

In planimetry, the outline of the cyclist and bicycle is traced with a polar planimeter, and a triangulation method is used to calculate the enclosed area (Olds & Olive, 1999). Olds and Olive (1999) compared a method based on weighing pictures and planimetry while measuring  $A_p$  cyclist in three positions: i) *Upright position*: where the torso is upright with the hands placed near the stem of the handlebars; ii) *Dropped position*: partially bent over torso position with hands on the drop portion of the handlebars and elbows fully extended; and iii) *Aerodynamic position*: where the arms are resting on aero-handlebars. The authors observed a significant mean difference ( $< 3.3\%$ ) between the projected frontal areas determined by the two methods. Both methods were extremely reliable but weighing photographs gave a more precise result than the planimetry-based method. The mean differences were 0.25% vs. 2.90% respectively for the weighing photographs and planimetry.

### *Digitalisation*

Like the method of weighing photographs, the digitising method (Barelle et al., 2010; Debraux et al., 2009; Dorel et al., 2005; Heil, 2001, 2002) requires the use of a calibration frame with a known area placed near the cyclist and bicycle. However, this digital method does not require the cutting of photographs; instead, it consists of digitalising a paper picture with the help of a digitiser (Heil, 2001), or with a computer-based image analysis software application (e.g. Scion Image Release Alpha 4.0.3.0.2 for Windows, Scion Corporation, Frederick, Md., USA or ImageJ software) if the pictures are in numerical format (Barelle et al., 2010; Debraux et al., 2009; Dorel et al., 2005; Heil, 2002). Accurate preparation is needed in order to be able to use numerical pictures. The zones to be measured must be darkened. This can be done in two ways, either by converting the picture into a black and white file using computer-based imaging software (e.g. Gimp, Adobe Photoshop) (Debraux et al., 2009) or by using a light placed behind the cyclist and bicycle (Dorel et al., 2005).

In a computer-based image analysis software application (e.g. Scion Image Release Alpha 4.0.3.0.2 for Windows, Scion Corporation, Frederick, Md., USA), the black and white image is imported, and the zones of the cyclist with the bicycle and the calibration frame are

selected (see Figure 7B). The software measures the number of pixels included in the zones. The actual projected frontal area in square metres of the digitised image is obtained by determining the ratio of pixels of the two zones then multiplying this ratio by the actual known area of the calibration frame. To measure only the cyclist projected frontal area, it is necessary to take a picture of the cyclist and bicycle, and one of the bicycle alone, then manually subtract the pixel count from the picture of the bicycle alone from the pixel count of the picture representing both cyclist and bicycle.

The digitising method needs a personal computer (but the software is free and easy to use) and a digital camera or a scanner to digitise the printed photographs. However, it requires the investigator to correct the photographs (e.g. darken the measured zone, change the extension of the image file) before opening them in the software Scion Image, which will take time and practice. This method is valid in comparison with the method of weighing photographs (Heil, 2001; Debraux et al., 2009).

#### *Method based on computer-aided design (CAD) software*

The methods based on CAD software do not require a calibration zone to be placed near the cyclist and can be used in actual conditions. The calibration is assessed by entering a known distance (vertical or horizontal) corresponding to a distance in the photographs (e.g. the width of the handlebars, the height of the front wheel) in the software (Figure 7C). The digital photographs are opened in CAD software. The outlines of the area measured are traced with a spline curve tool in a 2D plane. The software calculates the area enclosed (Debraux et al., 2009). This method is valid in comparison with the method of weighing photographs and reliable (CV = 0.1%) (Debraux et al., 2009). It is a fast method, but it needs a personal computer and CAD software, which are both relatively expensive. As this method can be used in actual conditions, it is possible to test the aerodynamic drag of different positions at a lower cost by using it together with linear regression analysis or towing.

Among the different methods described to assess the projected frontal area, the digitalisation method and the methods based on a CAD software are better adapted for the digital image format. Planimetry and the method of weighing photographs both require more procedures and more time for a measurement which could be done in five minutes utilising the new digital methods (Debraux et al., 2009). However, all these methods are reliable, and there is no significant difference between weighing photographs, digitalisation, and the method based on CAD software (Heil, 2001; Debraux et al., 2009). The new methods are simply faster and more convenient.

Nevertheless, all these methods have in common the need to take a photograph of the cyclist-bicycle system. Since the measurement of the projected frontal area is dependent on the photograph, the placement of the calibration frame and the optical calibration of the digital camera can be source of errors. To study these measurement errors, Olds and Olive (1999) determined the effects on the projected frontal area of the calibration frame position and the position of the camera relative to the cyclist-bicycle system. The authors made some recommendations in order to standardise the measurement protocol of the projected frontal area using a calibration frame, or not: i) The frontal plane of the calibration frame has to be located approximately midway between the cyclist's hip and shoulder. Olds and Olive (1999) showed that when the calibration frame was moved back to the rear wheel-tip, the projected frontal area increased by 61%, and when it was placed at the front wheel-tip, the projected frontal area decreased by 46%; ii) The digital camera has to be directed straight towards the cyclist at the height of the handlebars in the axis of the bicycle. An angular deviation of 10° of the digital camera could induce a 7.5% increase of the projected frontal area measure

(Olds & Olive, 1999); and iii) The digital camera has to be located at least 5 metres away from the cyclist-bicycle system. This is to minimise distortion due to focal length and the differences in apparent size of the parts of the cyclist closer and further from the digital camera (Olds & Olive, 1999).

### **How to minimise aerodynamic drag**

In cycling, aerodynamic drag is composed of two forms of drag: pressure and skin-friction drag (Faria, 1992; Millet & Candau, 2002). Pressure drag is the most important part of aerodynamic drag. It represents the difference of air pressure that exists between the front and rear of a moving body. Within a fluid, a moving body creates a boundary layer due to the fluid pressure on the body and leads to backward turbulence resulting in pressure drag. Pressure drag is mainly dependent on the general size and shape of the body. Skin-friction drag is the resistance generated by the friction of fluid molecules directly on the surface of the body in motion. It increases with the size and roughness of the body surface (Millet & Candau, 2002).

As explained previously, the effective frontal area is the determinant parameter of the cyclist-bicycle system aerodynamic. Both general size and shape of the moving body affect the effective frontal area, and can be decreased in different ways according to Kyle and Burke (1984) and Millet and Candau (2002). A cyclist can lower aerodynamic drag in reducing the projected frontal area. The angle between the trunk and the ground is important, the nearer the angle to 0 degrees, the more the projected frontal area decreases (Heil, 2001). Faria (1992) reported a decrease of 20% of the aerodynamic drag when the cyclist's elbows are bent with the torso nearly parallel to the ground. The position of the arms is a supplementary factor to modify in order to enhance the projected frontal area. A decrease of 28% in aerodynamic drag was observed when the hands were on the centre of the upper handlebars, trunk resting on the hands, crank parallel to the ground (Faria, 1992). The hands can be placed forwards in relation to the body in using aero-handlebars, and this can increase comfort and decrease the projected frontal area. Moreover, Berry et al. (1994) did not find significant differences between aero-handlebars and standard racing handlebars in terms of exhaustion, power output and oxygen consumption.

The effects of the moving cyclist-bicycle system shape on the aerodynamic drag are quantified by the drag coefficient (di Prampero, 1986). To reduce the drag coefficient, the shape of the moving body has to be streamlined. The position, an aerodynamic bicycle frame, aerodynamic helmet, aerodynamic wheels (Tew & Sayers, 1999), and clothes and accessories can significantly reduce the drag coefficient (Faria, 1992; Faria et al., 2005). Tew and Sayers (1999) showed that aerodynamic wheels could reduce the axial drag of up to 50% in comparison with the spoked wheels. Different techniques exist to enhance the effective frontal area for the cyclist-bicycle system, and every improvement must be tested and quantified to find out whether the decrease in effective frontal area can save significant time in actual racing conditions (e.g. time-trials) (Atkinson et al., 2007). This is why mathematical models of cycling performance are necessary to simulate mechanical power output, which depends on many parameters.

### **Importance of the effective frontal area in modelling cycling performance**

A theoretical model can provide a helpful simulation tool for researchers, coaches, and cyclists who do not have access to the technologies indicated above (e.g. powermeter, computer). Indeed, a model permits the effect on cycling performance of physiological

changes, biomechanical, anthropometric, and environmental factors to be predicted (Olds et al., 1993). Many authors have established a mathematical cycling model (e.g. Atkinson et al., 2007; Broker et al., 1999; di Prampero et al., 1979; Heil et al., 2001; Martin et al., 2006; Nevill et al., 2006; Olds, 1998, 2001; Olds et al., 1993, 1995; Padilla et al., 2000), most including terms for power output produced by the cyclist and power required to overcome aerodynamic drag, rolling resistance, and other parameters (Martin et al., 2006). At displacement velocity greater than 14 m/s where the aerodynamic drag is about 90% of the total resistive forces, according to Equations 1 and 2, it can be assumed that the mechanical power output is proportional to the product of aerodynamic drag and velocity. The mechanical power necessary to drive the cyclist-bicycle system through the air will increase with the cube of the velocity (Faria, 1992).

Gonzales-Haro et al. (2007) and (2008) have compared nine theoretical models for estimating the power output in cycling using the SRM powermeter in a velodrome. The most important variables in these models are: velocity, mass of the cyclist-bicycle system, and aerodynamic variables: the projected frontal area and the drag coefficient. Other secondary variables are the slope, rolling coefficient and climatic conditions (barometric pressure of the fluid and temperature). Gonzales-Haro et al. (2007) found the equations of di Prampero et al. (1979) and Candau et al. (1999) the best estimates of power output in comparison with measurements with the SRM powermeter, whereas Gonzales-Haro et al. (2008) found the equation of Olds et al. (1995) best to estimate peak power output because of the few variables to measure.

As on level ground, at racing speeds greater than 14 m/s, aerodynamic drag represents about 90% of the overall resistive forces (Candau et al., 1999; di Prampero, 2000; Martin et al., 2006; Millet & Candau, 2002) and consideration of the effective frontal area in a mathematical model is important. Its estimation can strongly influence the model. However, some simulations did not take it in account or are based on approximation (Table III).

Olds et al. (1995) established a relationship between the projected frontal area and the body surface area considering that the projected frontal area is a constant fraction of the body surface area in a given position:

$$A_p = 0.3176 \cdot A_{BSA} - 0.1478 \quad (21)$$

These equations do not take into account the differences intra- and inter-individual for the same position on the bicycle, or different bicycles. In these authors' model, the drag coefficient was a constant and equal to 0.592. For comparison, we estimate the projected frontal area according to Olds et al. (1995) and we measure the projected frontal area using the CAD method (Debraux et al., 2009). The revisited equation of the body surface area by Shuter and Aslani (2000) was used (see Equation 5), where the body surface area is expressed in square metres but the body height is expressed in cm. Table IV presents the results of the difference between the two methods on seven cyclists in traditional aerodynamic position. The mean results show an increase of 0,021 m<sup>2</sup> (+4.9%) for the projected frontal area with the method of Olds et al. (1995). The two methods are compared with a paired t-test and the difference is significant ( $p < 0.05$ ). However, additional studies should be performed on the accuracy of the methods for the projected frontal area determination.

In order to be valid, the mathematical model for an estimation of the projected frontal area must consider various parameters (e.g. the position of the cyclist, the wearing of a helmet). In this way, the drag coefficient that changes with position and velocity has to be determined. Martin et al. (2006) found that the effective frontal area values determined in field trials with the SRM powermeter were similar to those measured in the wind tunnel. This method is very useful to assess the effective frontal area in actual conditions as routine and the cyclists can

Table III. Mathematical expression of the aerodynamic parameters in modelling of the power output

Study	Method of calculation of the aerodynamic parameters
Whitt (1971)	$A_p$ has to be determined
di Prampero et al. (1979)	Based on a percentage of $A_{BSA}$ with $A_{BSA} = 0.007184 \cdot m_b^{0.425} \cdot h_b^{0.725}$
Kyle (1991)	$C_D = 0.8$ $A_p$ has to be determined
Menard (1992)	$SC_x = 0.259 \text{ m}^2$ $SC_{xv} = 0.012 \text{ m}^2$
Olds et al. (1993)	Based on a percentage of $A_{BSA}$ $A_{BSA} = 0.007184 \cdot m_b^{0.425} \cdot h_b^{0.725}$ $CF_A = A_{BSA} / 1.77$
Broker (1994)	$K_1 = K_d \cdot K_{po} \cdot K_b \cdot K_c \cdot K_h$ $A_p$ has to be determined
Olds et al. (1995)	$C_D = 0.592$ $A_b = 0.3176 \cdot A_{BSA} - 0.1478$ Total $A_p = 0.4147 \cdot (A_b / 1.771) + 0.1159$
Candau et al. (1999)	$A_p C_D = 0.333 \text{ m}^2$
Shuter and Aslani (2000)	$A_{BSA}(\text{m}^2) = 0.00949 \cdot h_b^{0.655} \cdot m_b^{0.441}$ with $h_b$ in cm
Heil (2001)	$A_p = 0.00433 \cdot STA^{0.172} \cdot TA^{0.096} \cdot m_b^{0.762}$ $C_D = 4.45 \cdot m_b^{-0.45}$
Faria et al. (2005)	$FA = 0.0293 \cdot h_b^{0.725} \cdot m_b^{0.425} + 0.0604$
Martin et al. (2006)	$A_p C_D$ has to be determined
Barelle et al. (2010)	$A_p = 0.107 \cdot h_b^{1.6858} + (0.329 (L \cdot \sin \alpha_1)^2 - 0.137 \cdot (L \cdot \sin \alpha_1))$ $A_p = 0.045 \cdot h_b^{1.15} \cdot m_b^{0.2794} + (0.329 (L \cdot \sin \alpha_1)^2 - 0.137 \cdot (L \cdot \sin \alpha_1))$

$A_p$  = Projected frontal area ( $\text{m}^2$ );  $A_b$  = Projected frontal area of the body ( $\text{m}^2$ );  $A_{BSA}$  = Body surface area ( $\text{m}^2$ );  $m_b$  = Body mass (kg);  $h_b$  = Body height (m);  $C_D$  = Coefficient of drag;  $SC_x$  = Coefficient of air penetration determined in wind tunnel ( $\text{m}^2$ );  $SC_{xv}$  = Wheel's coefficient of air penetration determined in wind tunnel ( $\text{m}^2$ );  $CF_A$  = Correction factor for body surface area ( $\text{m}^2$ );  $K_1$  = Aerodynamic factor;  $K_d$  = Air density;  $K_{po}$  = Rider position;  $K_b$  = Cycle components;  $K_c$  = Clothing;  $K_h$  = Handlebar type;  $FA$  = The total frontal area of the cyclist in the aerodynamic position with Aero-Handlebars ( $\text{m}^2$ );  $L$  = Length of a time-trial helmet (m);  $\alpha_1$  = Helmet inclination on the horizontal (degree).

Table IV. Comparison of the estimation of  $A_p$  with the equation developed by Olds et al. (1995) using  $A_{BSA}$  calculated according Shuter and Aslani (2000) and the measure of  $A_p$  with the CAD method (Debraux et al., 2009) for cyclists in traditional aerodynamic position with modern bicycle

Subjects	$h_b$ (m)	$m_b$ (kg)	$A_p$ ( $\text{m}^2$ ) Olds et al. (1995)	$A_p$ ( $\text{m}^2$ ) Debraux et al. (2009)
Subject 1	1.74	78	0.456	0.406
Subject 2	1.81	70	0.443	0.425
Subject 3	1.90	75	0.481	0.424
Subject 4	1.85	72	0.459	0.425
Subject 5	1.70	64	0.397	0.385
Subject 6	1.80	64	0.417	0.416
Subject 7	1.75	65	0.412	0.401
Subject 8	1.80	75	0.459	0.461
Subject 9	1.75	91	0.501	0.488
$M \pm SD$	$1.79 \pm 0.06$	$72.7 \pm 8.6$	$0.447^* \pm 0.034$	$0.426^* \pm 0.031$

\*Significant difference at  $p < 0.05$

$A_p$  = Projected frontal area ( $\text{m}^2$ );  $A_{BSA}$  = Body surface area ( $\text{m}^2$ );  $h_b$  = Body height (m);  $m_b$  = Body mass (kg).

test several positions and bicycles. Considering the mathematical model of Olds et al. (1995) as the best estimate of the peak power output (Gonzales-Haro et al., 2008), it could be more appropriate to use this model with the effective frontal area estimated by the method of linear regression analysis.

## Conclusion

The effective frontal area is the most important parameter to characterise aerodynamic drag. The techniques of estimation of the effective frontal area are now well recognised in cycling, and this parameter can be reliably evaluated in laboratory or actual conditions. However, although the projected frontal area is a well-known easily quantifiable factor, the variation of the drag coefficient is more complex. Its evolution as a function of velocity is still difficult to understand fully. More research will be necessary to study the characteristics of drag coefficient variation. New methods such as computational fluid dynamics could be a great help in achieving this. Knowledge of these parameters can be very helpful in developing theoretical models. A mathematical simulation can provide an estimation of performance, and is thus a tool for cyclists, coaches and scientists. Moreover, if the effective frontal area can be accurately estimated, the model will be more reliable.

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