Aerodynamics of a cycling team in a time trial: does the cyclist at the front benefit?

To cite this article: A Íñiguez-de-la Torre and J Íñiguez 2009 *Eur. J. Phys.* **30** 1365

IOP PUBLISHING EUROPEAN JOURNAL OF PHYSICS

Eur. J. Phys. **30** (2009) 1365–1369 doi:10.1088/0143-0807/30/6/014

Aerodynamics of a cycling team in a time trial: does the cyclist at the front benefit?

A Íñiguez-de-la Torre and J Íñiguez

Departamento de Física Aplicada, Universidad de Salamanca, E37071, Spain

E-mail: nacho@usal.es

Received 24 July 2009, in final form 10 August 2009
Published 5 October 2009
Online at stacks.iop.org/EJP/30/1365

Abstract
When seasonal journeys take place in nature, birds and fishes migrate in groups. This provides them not only with security but also a considerable saving of energy. The power they need to travel requires overcoming aerodynamic or hydrodynamic drag forces, which can be substantially reduced when the group travels in an optimal arrangement. Also in this area, humans imitate nature, which is especially evident in the practice of outdoor sports and motor competitions. Cycle races, in which speeds of up to 15 m s^{-1} are frequent, offer great opportunities to appreciate the advantage of travelling in a group. Here we present a brief analysis of the aerodynamics of a cycling team in a time-trial challenge, showing how each rider is favoured according to his position in the group. We conclude that the artificial tail wind created by the team also benefits the cyclist at the front by about 5%.

(Some figures in this article are in colour only in the electronic version)

One of the most important difficulties in physics teaching is the little interest that many students show in several fields of undergraduate physics programmes. It is essential to dedicate our efforts to stimulating motivation by looking for attractive subjects, applications, problems, practical exercises and complementary activities. In some fields, such as fluid physics or aerodynamics, these difficulties are paramount, and to choose examples related to sports physics could be an ideal option to encourage students' enthusiasm. Cycling is a very popular sport among them and may offer an ideal candidate in this respect. Speeds close to 15 m s^{-1} are not uncommon in cycle races, which is why aerodynamic considerations are extremely important. Here, a brief experimental and computational study on the aerodynamics of a cycling team in a time-trial race is presented. Special attention is paid to calculations of the power that each cyclist saves depending on his place in the team, and our results are compared with data from the individual time-trial (ITT) and the team time-trial (TTT) stages of the *Tour de France* for 2004 and 2009. In both cases, when comparing the racing of a rider alone

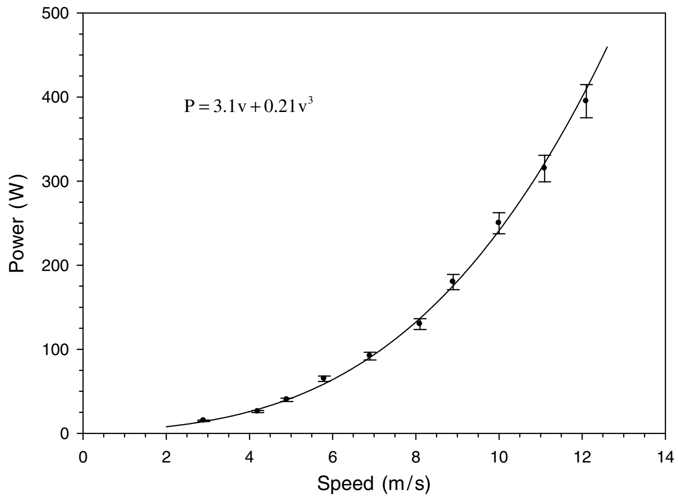

Figure 1. Measurements of the power developed by a solitary cyclist of 79 kg rolling along a good horizontal road in the absence of wind. Data were obtained with the help of a *Polar Power Output Sensor* [9]. The curve corresponds to equation (2) with $\alpha \approx 3.1$ N and $\beta \approx 0.21$ kg m^{-1}.

with respect to that corresponding to the team, speed increments of up to 10% and more are reached. There are a very few books in the literature addressing the field of aerodynamics in cycling [1], although on the Web, some sites devoted to analytical calculations in this area can be seen [2]. Some recent works on the physics of cycling can also be found [3–7].

It is very difficult to perform analytical calculations of the power developed by cyclists when they are travelling in a group. This is only possible for a single rider. In this case, the total power (rolling and aerodynamics) along a horizontal road in the absence of wind is written as

$$P = Fv = (F_R + F_A)v, \tag{1}$$

where F_R and F_A, respectively, represent the rolling friction and the aerodynamic drag forces, and v is the speed of the cyclist. Thus, we can write [1, 8]

$$P = \mu g m\, v + \tfrac{1}{2}\rho C S\, v^3 = \alpha v + \beta v^3, \tag{2}$$

where $\mu \lesssim 0.004$ is the rolling friction coefficient, $g = 9.8$ m s^{-2} and m the mass of the cyclist and bicycle together. The air density is ρ, the aerodynamic coefficient is C and the cross-sectional area of the cyclist and bicycle is S.

While α takes values around 2.6–3.2 N, the β coefficient ranges from 0.18 kg m^{-1}, in high competition cycling (for a medium-sized cyclist wearing high performance clothing and riding a time-trial bicycle), up to 0.22 kg m^{-1} for an amateur cyclist rolling in a semi-inclined position on the bicycle [1, 3]. Equation (2) shows good agreement with our experimental results as can be seen in figure 1. Our power measurements in a small cycling group were made using the Conconi test (quasi-linear relation pulse versus power in the aerobic region) and a heart rate monitor and were verified *in situ* with the help of a *Polar Power Output Sensor* [9].

Powers of several hundred watt at speeds of 10–15 m s^{-1} clearly justify the importance of developing refined team strategies with a view to saving energy: rolling in pace line, forming compact groups (the so-called peloton) or arranging the riders diagonally when lateral wind blows (the well-known echelons) are the most frequent.

When cyclists travel in a group, the value of the β coefficient in equation (2) is strongly dependent on the geometry of the team (number and size of riders and gap between the individuals), and it also takes different values for each rider depending on his place in the group. Therefore, only individual power measurements would be able to provide information about the amount of energy that each cyclist uses up. In order to extend our experimental results to a larger group of cyclists, we resorted to performing a numerical simulation of the aerodynamics of cycling in a virtual wind tunnel.

Although a realistic analysis of the complex geometry of a cyclist would require using 3D fluid dynamics numerical simulation, the difficulties in its modelling as well as the excessive price of that software counsel us to try a simpler analysis by means of a 2D numerical simulation. Therefore, we have used a 2D virtual wind tunnel [10] and a simplified model of the cyclists, just consisting of elliptic shapes that we have optimized to reproduce within 5% our experimental results obtained for groups composed of five riders rolling in pace line with a gap between them of 20 cm. In this way, we were able to obtain good approximations of the aerodynamic characteristics (air pressure, temperature, density and wind speed) of larger groups. To illustrate our results, the wind plot for a single cyclist rolling alone is in figure 2, while the case of a team composed of three cyclists is shown in figure 3. The power developed by the cyclists based on their position in the group is seen in table 1.

As anticipated, it may be observed that the cyclists who travel behind have to make less effort but it should be noted that the cyclist in front also benefits from the presence of the rest of the team; the artificial tail wind also helps him by about 5%. The aerodynamic coefficient is effectively reduced. This result, unexpected for many people, is known, or at least suspected, by cyclists accustomed to rolling in groups at high speeds because all the effects are enhanced as speed increases.

As expected, the advantage of cycling in a well-coordinated group increased rapidly with the number of components, and our study showed that the ideal number of a team is five or six cyclists and that the mean value of the force diminishes to 70% of that corresponding to a single cyclist rolling alone. Indeed, when the size of the group grows at the time of taking turns as leader (which reduces the effective number of riders), the difficulties in coordination increase, and correctly preserving the gap between the bicycle wheels becomes difficult. Certain other complications involved in the difficulties of maintaining the pace line are the presence of curves, side wind or the different size and power of the cyclists. Finally, it should be noted that it is not easy to continuously preserve such a small separation between cyclists (10–20 cm) when rolling at speeds such as 10–15 m s^{-1}.

In the TTT of the *Tour de France* 2004, the team of Lance Armstrong travelled at 14.92 m s^{-1}, whereas in the ITT he rolled at an average speed of 13.72 m s^{-1}, over similar roads in the length and profile. More recently, in the TTT of the 2009 edition of the *Tour*, the average speed of the *Astana* team was 13.98 m s^{-1}, although unfortunately the characteristics of the stage were not appropriate for the practice of cycling in a well-synchronized team. In contrast, the speed of Alberto Contador in the ITT was 13.75 m s^{-1}, practically identical to the speed of Armstrong in the 2004 ITT. Upon comparing these results with our calculations, it may be concluded that travelling in a group in a real stage is not as advantageous as the calculation predicts, doubtless due to the reasons alleged in the previous paragraph.

Here is a nice example to explain some concepts of elementary aerodynamics for undergraduate students of physics or engineering at intermediate level. Examples related to sports physics always constitute a good option to encourage the motivation of the students.

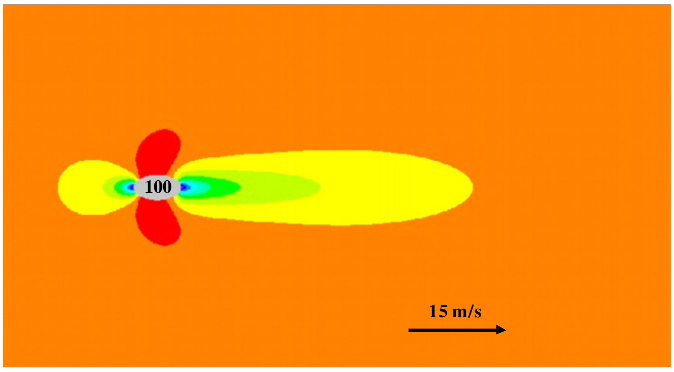

Figure 2. Top-view of a simplified model of a 2D computational air-speed flow picture for a single cyclist rolling alone in a virtual wind tunnel at 15 m s^{-1}. The aerodynamic drag force is normalized to $F = 100$. Warm/cool colours represent high/low air-speeds with respect to the cyclist.

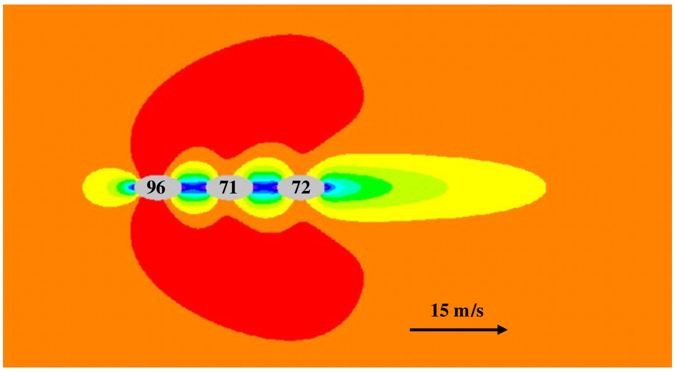

Figure 3. Top-view of a computational air-speed flow picture for a team composed of three cyclists when they travel in a virtual wind tunnel at 15 m s^{-1} in pace line. The aerodynamic drag forces are respectively 96, 71 and 72% of that corresponding to a single rider rolling alone. The purple (darkest) colour corresponds to the artificial tail wind.

Table 1. Forces that each cyclist develops when travelling in pace line as a function of his place in the group.

Team size	$F1$	$F2$	$F2$	$F4$	$F5$	$F6$	$F7$	$F8$	$F8$	$\langle F \rangle$
1	100									100
2	96	74								85
3	96	71	72							80
4	96	69	68	70						76
5	95	68	67	67	69					73
6	95	68	67	67	67	69				72
7	95	67	66	66	66	66	68			71
8	95	67	66	66	66	66	66	68		70
9	95	67	66	66	66	66	66	66	68	70

The values are normalized ($F = 100$) to that corresponding to a cyclist rolling alone. The last column shows the average value of the force developed by the riders of the team as a function of the group size.

References

[1] Wilson D G 2004 *Bicycling Science* 3rd edn (Cambridge, MA: MIT Press)
[2] For a compilation see http://www.sheldonbrown.com/rinard/aero/index.htm or http://www.exploratorium.edu/cycling/aerodynamics1.html
[3] di Prampero P E, Cortili G, Mognoni P and Saibene F 1979 Equation of motion of a cyclist *J. Appl. Physiol.* **47** 201–6
[4] Cummings A 1997 Cycling in the wind *Eur. J. Phys.* **18** 176–9
[5] Hannas B L and Goff J E 2004 Model of the 2003 Tour de France *Am. J. Phys.* **72** 575–8
[6] Hannas B L and Goff J E 2005 Inclined-plane model of the 2004 Tour de France *Eur. J. Phys.* **26** 251–9
[7] Íñiguez-de-la-Torre I and Íñiguez J 2006 Cycling and wind: does sidewind brake? *Eur. J. Phys.* **27** 71–4
[8] Landau L D and Lifshitz E M 1982 *Fluid Mechanics* 2nd edn (Oxford: Pergamon)
[9] Polar Available online at http://www.polar.fi/polar/entry.html
[10] MicroCFD is a Windows-based program on computational fluid dynamics for analyzing 2D planar and axisymmetric problems on subsonic, transonic, and supersonic air flow. Visualization is provided through colour maps of local speed, density, pressure, and temperature Available at http://www.microcfd.com/index.htm