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# Human-Powered Vehicles – Aerodynamics of Cycling

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## 1. Introduction

Human-powered transport can be defined as that type of transport that only uses the human muscle power. When considering non-vehicular human-powered transport, it should to be indicated that it exists from the beginning of the human history (walking, running, swimming or climbing to trees). On the contrary, if we refer to vehicular transport we must necessary mention the wheel invention. It is superfluous to remark that the wheel is the most essential element of any form of vehicular land transportation and perhaps the greatest mechanical invention of the human civilization. Although archaeologists say that the wheel was discovered around 8000 BC in Asia, today is generally accepted that the oldest wheel known was discovered around the year 3500 BC in Sumeria, part of modern day Iraq. It was manufactured of slats of wood linked together. The wheel allowed the people to travel with greater speed and efficiency than walking: In a first step with the help of animal-powered rolled chariots and from the 19th century in human-powered vehicles also.

The most efficient human-powered vehicle is obviously the bicycle. Modern technology allows manufacturing high efficiency bicycles permitting to extraordinarily increase the human muscle power effectiveness. During the last century the development of petrol, gasoil and electric engines have increased load capacity and speed in many kinds of vehicles in such a manner that human-powered transport (mostly the bicycle) has been clearly relegate. Fortunately, in recent days we assist to a renaissance of cycling due to a variety of reasons as can be low cost, physical exercise, healthful sport, leisure or ecological and sustainable transport in the center of our populous cities.

It is interesting to remark that today is frequent to find papers devoted to the study of the stability of the bicycle. It seems clear that the gyroscopic contribution is not the main assistance to guarantee the stability of a bicycle, but however the problem is not completely solved yet [Jones, 1970; Cleary et al., 2011; Kooijman et al., 2011].

The scarcity of available power in human-powered machines is the main handicap for its effective development. In order to be conscious of this fact we remember that any motorized conventional vehicle has power ranging from some kW to a few hundreds of kW, while the useful power of a human is about some hundreds of W. Let's say that for a person of 70 kg

Fig. 1. The “High-Wheel” bicycle, 1870

the metabolic consumption at rest corresponds to 80 W and when sitting (reading, writing or watching TV) he requires a surplus of 40 W, while to make usual home activities power ranging from 50 to 100 W must be added. Walking at 1 m/s speed develops 150 W of additional power, i.e. a total of 230 W approximately is required. When running at 4-5 m/s speed or speedily climbing a mountain in bicycle the power requirement is near 0.6 to 1 kW, which constitutes a quantity that only very well trained sportsmen can maintain during a few minutes. Higher powers can be exclusively developed during a few seconds, as a sprint (running or cycling) with peak power about 2 kW, or a fraction of a second, as can be an athletic jump with 4 kW [Lea & Febiger , 1991; Bent, 1978; Eriksen et al. 2009].

A simple comparison of these figures with the energy consumption of our civilization results very instructive. The mean value of the amount of petroleum in 2008 was 4.5 barrels per year and person, but varies a lot from country to country. That year, in the USA, people used about 25 barrels of oil per capita whereas in Nigeria or Phillipines the amount was only 2 or 3 barrels. Taking into account that a barrel of oil is equivalent to 6.1 GJ, it results very easy to obtain that a USA citizen spent in 2008 a mean power of 4850 W coming from fossil fuel (irrespectively of others energy sources as carbon, gas, nuclear, hydroelectric, solar, eolic…), which roughly corresponds to a quantity 50 times greater than the mean power (100 W) of a person [Indexmundi, 2011].

## 2. Different types of human-powered vehicles

There are a lot of human-powered vehicles. Some of them are designed for land transportation (bicycle, monocycle, tricycle, quadracycle, recumbent bicycle, tandem bicycle, taxi-cycle, skateboard, ice skating, skiing, handcar…), others for travel in water (canoe, gondola, pedal boat, hydro-bike, galley, submarine…) and others to fly (aircrafts, helicopters…). With the exception of research or recreational objectives, human-powered water and air vehicles must be considered of very minor importance when referring to useful transportation.

Anyway is interesting to emphasize that on 1988 a team of MIT students succeeded in a project called Daedalus (exclusively human-powered aircraft). It flew across the Mediterranean Sea from the Greek island of Crete to just a few meters from the coastline of the island of Santorini, using a set of bicycle pedals and a transmission chain (see Figure 3). Made largely of carbon-fiber composite and Mylar, it weighed just 31 kg. On its record flight, Daedalus travelled 115 km during 3 h 54 min across the sea before being buffeted by winds, breaking its tail spar and crashing into the waves just 7 meters offshore from its destination. The pilot, champion bicyclist Kanellos Kanellopoulos, could swim to shore unhurt. An identical craft used in the initial tests is on display at Boston's Museum of Science. The flight set the all-time records for duration and distance of a human-powered flight, handily beating the previous record of just under 36 km set by Gossamer Albatross in a crossing

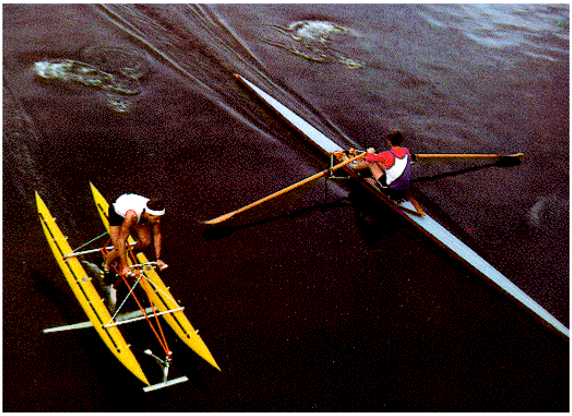

Fig. 2. Modern propulsion technology in water transportation

Fig. 3. Daedalus human-powered aircraft (Massachusetts Institute of Technology, Photo/NASA/Beasley)

of the English Channel in 1979. Some technical characteristics of Daedalus are: Wingspan 34 m, weight 32 kg, pilot weight 68 kg, fuel (water and sugar) 4 kg, speed 25 km/h, useful power of the pilot at the takeoff 900 W, at stationary regime 240 W, corresponding to a total power at stationary regime near 900 W (efficiency 27 %), amount of heat dissipation 660 W (600 via perspiration and 60 by radiation and convection). Finally, the fuel consumption was merely 1 liter of water with sugar 10 % and salts 0.1 % per hour [Chandler, 2008; Wikipedia, 2011].

Returning to less sophisticated transportation vehicles, it is clear that, as it was stated above, the most efficient human-powered land vehicle is the bicycle. It is also more efficient (up to 5 times) than walking. With energy amounts of 100 kJ a bicycle and rider can cover more than 5 km on a horizontal road at 20 km/h speed while a car can only travel about 200 m. Today the number of bicycles in the world is higher than one billion, which constitutes a good prove of its efficiency. Besides of the conventional upright bicycle, the recumbent bicycle is more efficient on horizontal and downing hills roads, as corresponds to its better aerodynamics. Electric bicycles, designed for one person and small load capacity, provide convenient local and short distance transportation. They work on the basis of power assistance; the electric engine helps the rider when pedaling. Power and speed in electric bicycles are limited to about 250 W and 25 km/h respectively. Electric bicycles are clean, quiet and offer advantages at very low cost instead acquiring an additional little car.


Fig. 4. Modern time-trial bicycle

Fig. 5. A recumbent bicycle

Fig. 6. A foldable electric bicycle

## 3. Efficiency of muscle power in human powered land vehicles: The bicycle

The high efficiency of a bicycle allows travelling long distances with very low energy cost. A healthy man can develop a useful power of 100 to 150 W and continuously travel near 25 km/h speed on a horizontal path, depending on the equipment, position of the rider and type of road. Instead, well-trained amateur cyclists can produce 300 W during an hour while first-class cyclists develop power as high as 1500 W during a few seconds or more than 300 W for several hours.

The power and speed that a cyclist can develop increase with the muscle mass, which is dependent on the weight and the body fat percentage. When considering a horizontal road, as we will show in the next paragraph, the main contribution to required power in cycling is related to overcome the aerodynamic drag. Taller cyclists will present a major wind resistance needing to produce more power while more compact riders will spend less power. This is the reason why it is no frequent to find first-class cyclists with thin and tall physic complexion. Remember that while the frontal area is quadratic with the linear size of the cyclist, the power (the muscle mass) is cubic, as we will see below. Tall and heavy riders have advantage when downing hills or in horizontal time trials and perhaps in the sprint and, however, short and light cyclists are benefit when climbing hills. Therefore, the optimum weight for an all-terrain cyclist is about 70 kg whereas for a sprinter is around 90 kg [Padilla et al., 2000].

It is to be remarked that the work developed by a muscle is equal to the force that exerts multiplied by the displacement. The force is proportional to the cross-sectional area of the muscle (the number of muscle fibers) whereas the displacement is proportional to the length of the muscular contraction. Consequently, the work developed by the muscle is proportional to its volume, its muscle mass. This is therefore the reason why the index of power by mass unit (W/kg), so used in any text of physiology of the sports, acquires all their importance. Here we can see a set of data corresponding to perhaps the most legendary climb of the *Tour de France*, the Alpe d' Huez. An ascent of 1073 m with an average gradient of 7.9 % and 21 emblematic curves. A well-trained cyclist of 75 kg and a bicycle about 8 kg cycling at 300 W would ascend at 12 km/h and would take in crowning it one hour and five minutes. Until the end of the 1990 the Alpe d' Huez was climbed between 45 and 42 minutes, i.e. at speed ranging from 17 to 19 km/h. For instance, P. Delgado with 64 kg raised it in 1989 at 18.6 km/h, developing about 380 W. Between years 1990 and 1997 there was a revolution that began with M. Indurain that rose in 1995 at 19.9 km/h, showing the record of 470 W for his 80 kg during 39 minutes. M. Pantani, 57 kg, destroyed this record in 1997 with an average speed of 20.9 km/h during 37.5 minutes. More recently the Alpe d' Huez is being climbed at speed below 20 km/h as F. Schleck, of 67 kg, which developed a mean power of 407 W ascending at a speed of 19.3 km/h and took little more than 40 minutes in the year 2006. It is very simple, the less weight, the less power the cyclist need to go at the same speed; as higher is the ratio W/kg of the cyclist higher is also his possibility to win [Cyclingforums, 2011].

The way in which the human body produces energy is very similar to the behavior of a fuel cell. In fact, the own human body can be considered as the oldest and most refined fuel cell the man uses, where foods are catalytically oxidized in an electrolyte (blood) to produce the necessary power for the whole physiological requirements. The chemical energy residing in the chemical bonds of fuel molecules is directly converted into other forms of useful energy without employing any intermediate thermal cycle.

Although this form to produce energy is very different from the case of the conventional thermal machines (Otto or Diesel engines), the mean efficiency of both systems is very similar ranging from 20 to 30 % [Sonawat et al., 1984].

The rest of the power is lost in the form of heat and, in the case of the cyclist, in non-useful power developed during pedaling. Then, the refrigeration as well as the hydration are very important. With the aim to improve the way in which the cyclist does his pedaling, several technological advances have been implemented years ago. Doubtless, the most important is the use of a variable gear ratio. Modern derailleur transmissions are 2-3 % more efficient than hub gear transmissions. With the purpose of guarantee the possibility of maintain a constant pedaling cadence near 85 rpm, modern competition bicycles use two or three chain-wheels and eleven rear sprockets. The correct election of the crank length is also important as well as the minimization of the waste power during time that pedals are at the top and bottom of their circular trajectory and the torque they produce is almost null (the dead spots). Use of non-circular pedaling, elliptical chain-wheels or more complex transmissions that allow controlling a variable relation between the angular speeds of pedals and chain-wheels during every turn, the well-known Rotor-Bike, are today frequent [Wilson, 2004; Rotorbike, 2011].

## 4. The aerodynamics of cycling

Some important aspects concerning the aerodynamics of cycling will be here summarized. While the wind resistance or aerodynamic drag is a well-known concept to all the people and particularly to cyclists when travelling at moderate speed, some other aerodynamic phenomena are less well-known. There are two main issues to be here addressed. The first one corresponds to the non-neutral effect of the sidewind while the other one is concerning with the flow effects that appear when cyclists are riding one behind the other and the consequent saving of energy the riders experience, including the cyclist who travels in first position.

It is well established that the presence of wind is crucial for the practice of numerous outdoor sports. Among them, the case of cycling competition is especially important because the speeds that are developed are perfectly comparable with moderate or strong winds, giving rise to a great variability in race times. Conversely, the sidewind seems to behave as neutral in the race, and nevertheless all the cyclists know the difficulties that it causes. Here we will show that the sidewind also produces an appreciable braking as a consequence of the quadratic dependence of the aerodynamic drag force on the air speed.

On the other hand, cycle races, in which speeds of up to 15 $ms^{-1}$ are frequent, offer great opportunities to appreciate the advantage of travelling in a group. We present a brief analysis of the aerodynamics of a cycling team in a time-trial challenge, showing how each rider is favored according to his position in the group. We conclude that the artificial tailwind created by the team also benefits the cyclist at the front by about 5 %. Also in this area, humans imitate nature. 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.

## 5. Cycling in the wind

The total force, $F_T$, that a cyclist exerts at a constant speed corresponds to three non-collinear quantities: the rolling resistance, $F_R$ (necessary to overcome mechanical friction), aerodynamic drag force, $F_D$ (to counteract the resistance force due to displacement through the air) and weight force, $F_W$ (which allows displacement on a non-horizontal road).

The rolling force, opposing the direction of motion, is proportional to the friction coefficient, $\mu$, and the normal component of the weight of the rider and bicycle:

$$F_R = \mu g(M+m)\cos\sigma \tag{1}$$

where $g$=9.8 $ms^{-2}$ represents gravitational acceleration; $M$ and $m$ correspond respectively to the mass of the rider and the bicycle, and σ represents the slope of the road.

This rolling force can be considered to be independent of the speed, and for a conventional racing bicycle with narrow tires (high pressure of about 0.7 MPa) rolling on a road in good conditions, the friction coefficient takes values close to 0.004 [di Prampero et al., 1979].

The aerodynamic drag force, in the direction of the air velocity relative to the cyclist, $\boldsymbol{V}_{\mathbf{rel}} = \boldsymbol{W} - \boldsymbol{V}$, (see figure 7), can be written as [Landau & Lifshitz, 1982]:

$$F_D = \frac{1}{2}\rho C_D A V_{rel}^2 \tag{2}$$

where the air density, $\rho$, at the standard temperature and pressure takes values of around 1.2 $kgm^{-3}$. $C_D$ is the drag coefficient, whose value is obtained as a function of the Reynolds number that we shall take as a constant for our purpose, irrespective of the angle between the directions of motion and wind. The projected area of the rider and bicycle, $A$, is also a function of the angle between the directions of motion and wind. The contribution of the bicycle is small and increases with the sidewind, while that corresponding to the cyclist is greater but diminishes with that wind. We can therefore disregard that dependence by

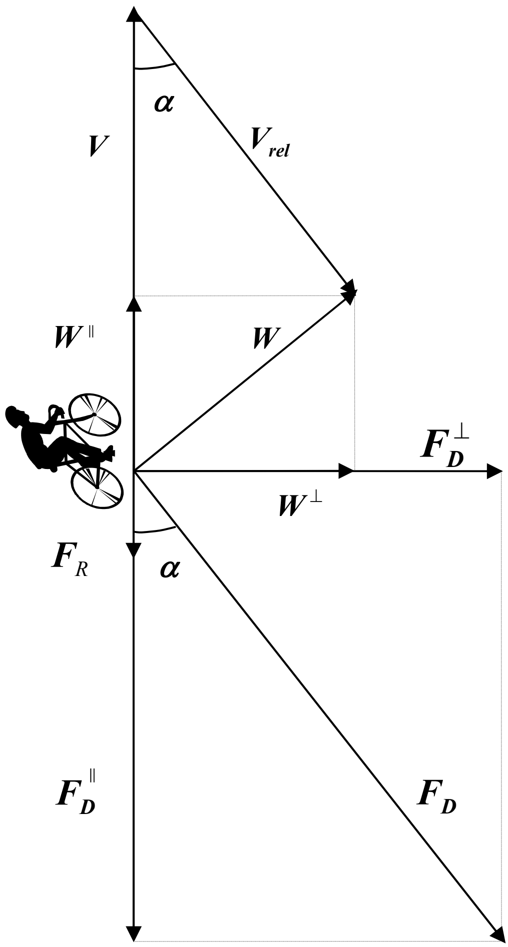


Fig. 7. Vectorial diagram of velocities and forces involved in cycling in the wind

taking $A$ as a constant. According to several authors, and considering a mean sized cyclist, wearing cyclist clothing, rolling alone, and alternating his position on the bicycle between the top and the bottom of the handlebar, equation (2) can be written as [Wilson, 2004]:

$$F_D \approx 0.24 V_{rel}^2 \tag{3}$$

where the constant $\rho C_D A/2 \approx 0.24$ is expressed in SI units, $Ns^2m^{-2}$. In this case, for our well-trained amateur cyclist, and assuming an air density of 1.2 $kgm^{-3}$, the product $C_D A$ takes a value around 0.4 $m^2$, but it is to be noted that this quantity is dramatically sensitive to small variations in the cyclist size and position on the bicycle. In table 1, a set of results on experimental drag studies on the aerodynamics of cycling are presented [Gross et al., 1983, Wilson, 1997].

| Bicycle type and rider position | Drag coefficient, $C_D$ | Frontal area ($m^2$) | $C_DA$ ($m^2$) | Force to overcome the air drag at 10 $ms^{-1}$ (N) |
|---|---|---|---|---|
| Upright commuting bicycle | 1.15 | 0.55 | 0.632 | 34.5 |
| Road bicycle and amateur cyclist | 1.0 | 0.4 | 0.4 | 22 |
| Competition bicycle and well-crouched rider | 0.88 | 0.36 | 0.32 | 17.6 |
| Road bicycle with simple fairing | 0.52 | 0.55 | 0.29 | 15.7 |
| Moser bicycle | 0.51 | 0.42 | 0.214 | 11.8 |
| M5 full faired low racer | 0.13 | 0.35 | 0.044 | 2.4 |

Table 1. Several data on aerodynamic of cycling

The effect of the position and geometry of the rider (prone or supine) and bicycle is extraordinary, but the use of high technology full fairings in recumbent bicycles is astonishing. It is possible reducing the required force to overcome an air resistance corresponding to a speed of 10 $ms^{-1}$ in more than one order of magnitude! Today, *The International Human Powered Vehicle Association* verifies the official speed records for recumbent bicycles. There are several well-defined modalities, the fastest of which is the "flying 200 m", a distance of 200 m from a flying start with a maximum allowable tailwind of 1.66 $ms^{-1}$. The current record is 133 $kmh^{-1}$, set by Sam Whittingham of Canada in a fully faired Varna Diablo front-wheel-drive recumbent low racer bicycle designed by George Georgiev [HPVA, 2011].

Finally, the weight force (opposing/parallel to the direction of motion) takes the form:

$$F_W = g(M+m)\sin\sigma \tag{4}$$

where the slope of the road, $\sigma$, is positive/negative for uphill/downhill inclinations. With the aim of placing emphasis on the effect of wind, we shall consider a horizontal road ($\sigma = 0$). Assuming a mass of $(M + m) = 81$ kg, and according to figure 1, we can write the two components of the total force (parallel, $F_T^{||}$, and perpendicular, $F_T^{\perp}$, to the motion):

$$F_T^{||} = 3.2 + 0.24 V_{rel}^2 \cos\alpha = 3.2 + 0.24 V_{rel}^2 \frac{V - W^{||}}{V_{rel}} \tag{5}$$

$$F_T^{\perp} = 0.24 V_{rel}^2 \sin\alpha = 0.24 V_{rel}^2 \frac{W^{\perp}}{V_{rel}} \tag{6}$$

where $\boldsymbol{V}$ and $\boldsymbol{W}$ are the velocities of the cyclist and the wind with respect to the road.

The rider's power is now calculated as:

$$P = -\mathbf{F_T} \cdot \mathbf{V} = \left(F_R + F_D^{||}\right) V = 3.2V + 0.24 V_{rel}^2 \frac{V - W^{||}}{V_{rel}} V \tag{7}$$

whereas the perpendicular force is simply balanced with the inclination of the cyclist.

To show the results of this model, we shall consider a cyclist rolling alone at 35 $kmh^{-1}$ (9.72 $ms^{-1}$) on a flat road. This corresponds to the speed that a well-trained amateur cyclist can develop during long periods of time in the absence of wind. According to equation (7), for $W = 0$, the required power is about 250 W, an amount that the present authors have verified personally with the help of a Polar Power Output sensor coupled to a Polar S725i heart rate monitor [Polar, 2011].

It corresponds to a very ingenious system that works by measuring the tension and the speed of the transmission chain. The first sensor calculates chain tension by determining the frequency of vibration as it passes over a magnetic sensor. It suffices to enter the chain weight per unit length and the chain length. Another sensor positioned on the rear pulley also works magnetically and measures chain speed. The power is readily calculated as the product of both quantities. Assuming that our cyclist is pedaling at a constant power of 250 W under a wind speed of 25 $kmh^{-1}$ (6.94 $ms^{-1}$), we summarize in table 1 the results for a rectilinear round-trip of 20 km considering no wind, a headwind, a tailwind or a sidewind. As expected, the duration of the trip increases with a headwind more than it decreases with a tailwind; over 20 km our cyclist loses 5 min and 33 s. But the most relevant result is the unexpected delay when cycling in a sidewind; over 20 km our cyclist increases his time by almost 3 min. Indeed, wind has a noteworthy effect on cycling [Íñiguez-de-la-Torre & Íñiguez, 2006].

| **Wind speed** **$W$ = 6.944 m/s** | **Equation (7)** **(250 W constant power)** | **Cyclist speed** **$V$** | **Round-trip duration** |
|---|---|---|---|
| No wind | $250 = 3.2V + 0.24V^3$ | 9.722 m/s (35 km/h) | 34 min 17 s |
| Headwind | $250 = 3.2V + 0.24(V + 6.94)^2 V$ | 5.870 m/s (21.13 km/h) | 39 min 50 s |
| Tailwind | $250 = 3.2V + 0.24(V - 6.94)^2 V$ | 14.576 m/s (52.47 km/h) | |
| Sidewind | $250 = 3.2V + 0.24(V^2 + 6.94^2)\dfrac{V}{\sqrt{V^2 + 6.94^2}}V$ | 9.006 m/s (32.42 km/h) | 37 min 1 s |

Table 2. Summary of the results for a 250 W cyclist under different wind conditions

With the purpose of describing the remarkable effect of an increasing lateral wind, the cyclist speed versus the sidewind speed for different power values is shown in figure 8. It paradoxical means that the crosswind leads to an increase in time. Intuitively, anyone would say that the lateral wind must be neutral. But all the cyclists well know its effect and recognize that this effect increases with their speed. Whereas an object at rest, $V \to 0$, would not be affected by this wind; when moving it will undergo an additional drag resistance due to the sidewind. To demonstrate this behavior, we shall neglect the rolling resistance in equation (5). For a sidewind of speed $W$, this is written as:

$$F_D^{||} = 0.24\left(V^2 + W^2\right)\cos\alpha = 0.24\, V\sqrt{V^2 + W^2} \qquad (8)$$

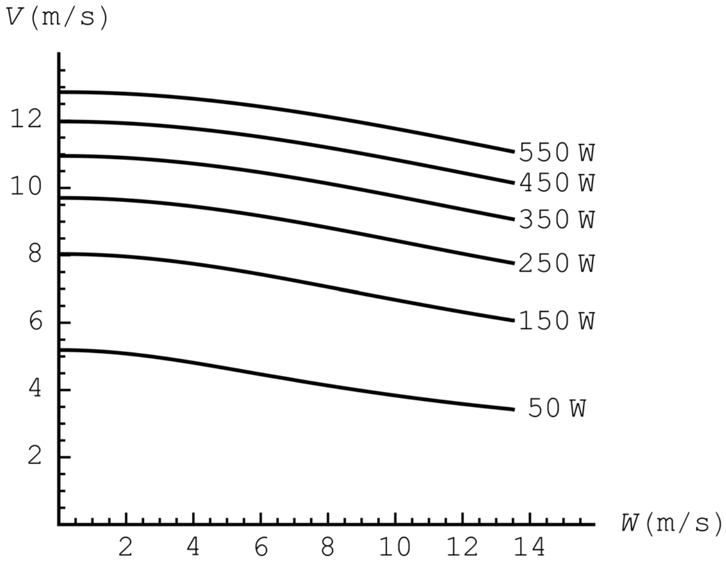


Fig. 8. Cyclist speed $V$ versus the sidewind speed $W$, at six different pedaling power rates

clearly showing that for $V \to 0$ the drag force is null, regardless of $W$. When $V$ is non-zero, this aerodynamic drag force is always opposite to the direction of motion and it increases with $V$ and $W$ because

$$V\sqrt{V^2 + W^2} \geq V^2 \tag{9}$$

which shows that these results are a simple consequence of the quadratic dependence of the aerodynamic drag force on the air speed. In order to clearly understand this statement, it should be noted that if the air speed dependence were linear, equation (8) would be written as:

$$F_D^{||} = K\sqrt{V^2 + W^2}\cos\alpha = K\,V \tag{10}$$

($K$ representing the coefficient of proportionality for the hypothetically linear behavior of the aerodynamic drag force versus the air speed) acting as if there was no sidewind.

## 6. Cycling in team

When birds fly in formation use less energy to migrate that when they do it alone. Birds in flocks can therefore fly for more distance than when travelling on their own (see a flock of birds in V-formation in figure 9). Recently, *The Observer* published an article entitled “Geese point the way to saving jet fuel: Planes flying in V-formation are more efficient and produce less carbon dioxide”, in such a manner that today the airline industry is looking to learn from them. In the future, our sky may perhaps not only have geese flying in V-formation but also passenger planes flying in group using less fuel and therefore producing less carbon dioxide emissions [McKie, 2009].

Fig. 9. Migration of a flock of geese V-formation

In 1914, a German researcher, Carl Wieselsberger, published a paper in which he showed that birds flying in V-formations use less energy to flap their wings than those on solo flights. He pointed out that when a bird flaps its wings it creates a current known as upwash; essentially, air lifts up and rises round the tips of the wings as they flap. Other birds, flying in the first one's wake, experience an updraft, allowing them to fly further. It is supported also by observations by French scientists who studied great white pelicans trained to fly behind an aircraft. The team, from the *Centre National de la Recherche Scientifique*, strapped instruments and transmitters to individual birds. This study revealed that the heart rate of the birds went down when they were flying together, and it also showed that they were able to glide more often when they flew in formation. Such experiments suggest that 25 large birds, such as pelicans or geese, flying in V-formation can travel 70 % further than flying alone. Many of the great migratory journeys, some covering thousands of miles, made by birds would be impossible without the energy-saving effects of group flight. Aviation engineers have now taken these discoveries to their logical conclusion and have proposed that aircrafts could fly in V-shaped groups so they can benefit from similar energy-saving effects.

This idea is the brainchild of researchers led by Professor Ilan Kroo, of Stanford University, California. In one calculation, the team envisaged three passenger jets leaving Los Angeles, Las Vegas and San Francisco airports en route to the east coast of the US. In the hypothetical exercise, the planes rendezvoused over Utah and then continued their journeys travelling in a V-formation, with planes taking turns to lead the formation. The group found that the aircrafts used 15 % less fuel and produced less carbon dioxide when flying in formation compared with solo performances. Such an approach could make significant inroads into the amount of carbon dioxide that is pumped into the atmosphere by planes.

However, critics have pointed to problems. Safety could be compromised by craft flying in tight formation, while coordinating departure times and schedules could become a major annoyance. The precision needed to coordinate just one aircraft to reach its destination safely is difficult enough, and air traffic controllers would be given a considerably larger headache if they had to coordinate the safe arrival several airplanes together. It also remains unproven as to how different weather conditions may affect V-formation flight efficiency. Although enabling flocks of passenger planes to fly in harmony like geese remain an arguably unlikely scenario, Chris Whitehead, a former hang glider pilot and teacher of the sport, remains skeptical of the California-based research. The local record holder and ex-Peak District team captain told that he specifically remembers how seagulls benefited by flying behind his glider, but other pilots coming in close proximity to one another would experience horrendous turbulence. It seems obvious that such difficulties could be only overcome with the help of more detailed research on their scheme.

As is well-known humans also imitate nature in this area; in many sports and motor competitions we apply the same aerodynamic and physic principles the birds use. The sport of cycling constitutes a beautiful example of how the members of a team can be helped to each other (see figure 10).

Fig. 10. Team time-trial in the *Tour de France*

In order to emphasize this issue, a brief experimental and computational study on the aerodynamics of a cycling team in a time-trial race is presented here. Special attention is paid to calculations of the power that each cyclist saves depending on his place in the team, and the results are compared with data from the individual time-trial (ITT) and the team time-trial (TTT) stages of the *Tour de France* for years of 2004 and 2009. In both cases, when comparing the racing of a rider alone with respect to that corresponding to the whole team, speed increments of up to 10 % and more are easily reached. There is a very few books in the literature addressing the field of aerodynamics in cycling, although on the web some sites devoted to analytical calculations in this area can be seen. Some recent works concerning aerodynamics and the basic physic principles of the sport of cycling can also be found [Wilson, 2004; di Prampero et al., 1979; Hannas & Goff 2004; Hannas & Goff, 2005; Landau & Lifshitz, 1982; Burke, 2003]. More details can be found in WebPages like [Bicycles Aerodynamics, 2011; Science of Cycling, 2011]

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, $F_R$, and aerodynamics, $F_D$) along a horizontal road with speed $V$, in the absence of wind is:

$$P = -\mathbf{F_T} \cdot \mathbf{V} = (F_R + F_D)V \tag{11}$$

This equation can be written as:

$$P = \mu g(M+m)V + \frac{1}{2}\rho C_D A V^3 = \beta V + \gamma V^3 \quad (12)$$

where $\mu \leq 0.004$ is the rolling friction coefficient. While $\beta$ takes values around 2.6 to 3.2 N, the $\gamma$ coefficient takes values from 0.18 $kgm^{-1}$, in high competition cycling (for a medium-sized cyclist wearing high performance clothing and riding a time-trial bicycle), up to 0.22 $kgm^{-1}$ for an amateur cyclist rolling in a semi-inclined position on the bicycle. Equation (11) shows good agreement with our experimental results as can be seen in figure 11.

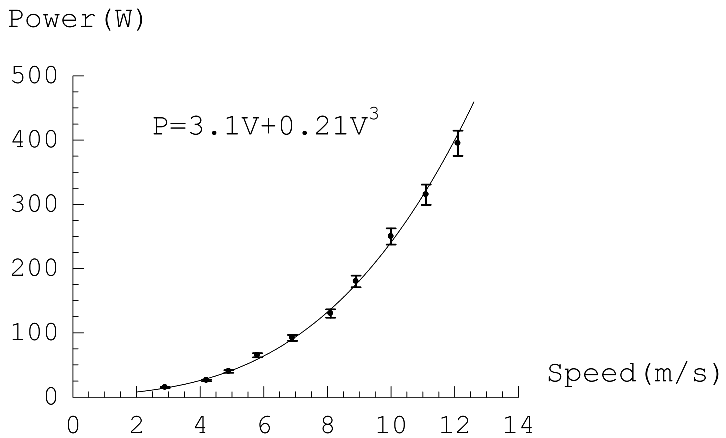


Fig. 11. Measurements of the power developed by a solitary cyclist of 79 kg rolling along a good horizontal road in the absence of wind. Data were obtained with the help of a Polar Power Output Sensor. Curve corresponds to equation (12) with $\beta \approx 3.1$ N and $\gamma \approx 0.21$ $kgm^{-1}$

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 [Polar, 2011].

Powers of several hundred watt at speeds of 10–15 $ms^{-1}$ 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 $\beta$ coefficient in equation (12) is strongly dependent on the geometry of the team (number and size of riders and gaps between them), 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 precise 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 modeling counsel us to try a simpler analysis by means of a 2D numerical simulation. Therefore, we have used a software of a 2D virtual wind tunnel 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.

The wind plot for a single cyclist rolling alone is in figure 12, while the case of a team composed of three cyclists is shown in figure 13. The power developed by the cyclists based on their position in the group is seen in table 3 [Íñiguez-de-la-Torre & Íñiguez, 2009]. The software here used, MicroCFD, is a Windows-based program on computational fluid dynamics for analyzing 2D planar and axisymmetric problems. Visualization is provided through color maps of local speed, density, pressure, and temperature [MicroCFD, 2011].

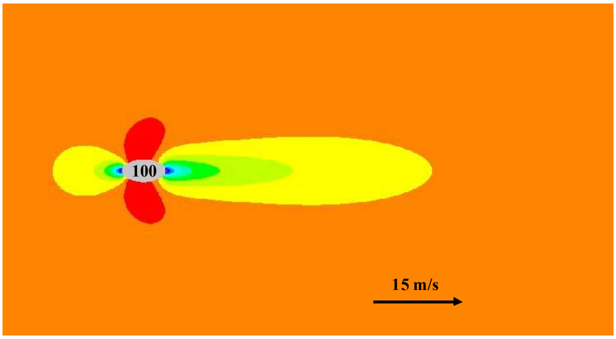


Fig. 12. Top-view of a simplified model of a 2D computational air-speed flow picture for a single cyclist rolling alone in a virtual wind tunnel at 15 $ms^{-1}$. The aerodynamic drag force is normalized to F = 100. Warm/cool colors represent high/low air-speeds

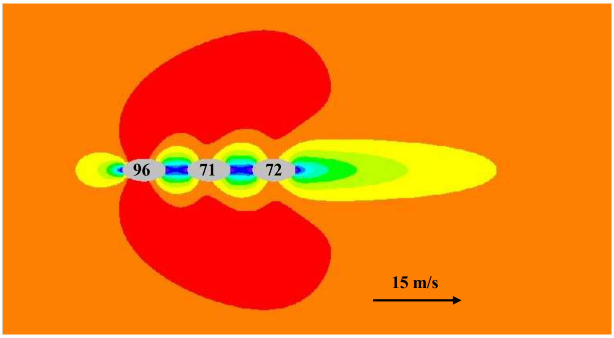


Fig. 13. Top-view of a computational air-speed flow picture for a team composed of three cyclists when they travel in a virtual wind tunnel at 15 $ms^{-1}$ in pace line. The aerodynamic drag forces are respectively 96, 71 and 72 % of that corresponding to a single rider rolling alone. The purple (darkest) color corresponds to the artificial tailwind

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 the front also benefits from the presence of the rest of the team; the artificial tailwind 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, sidewind 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 so high as 10–15 $ms^{-1}$.

In the TTT of the *Tour de France* 2004, the team of Lance Armstrong travelled at 14.92 $ms^{-1}$, whereas in the ITT he rolled at an average speed of 13.72 $ms^{-1}$, 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 $ms^{-1}$, 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 $ms^{-1}$, 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.

| Team size | $F_1$ | $F_2$ | $F_3$ | $F_4$ | $F_5$ | $F_6$ | $F_7$ | $F_8$ | $F_9$ | $\langle F \rangle$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 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 |

Table 3. Forces that each cyclist develops when travelling in pace line as a function of his place in the group. 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.

## 7. Conclusions

It has been demonstrated how the study of the aerodynamics in low speed vehicles is especially interesting when the available power is scarce. For that purpose, the analysis of the aerodynamics of cycling has been revealed like a fantastic example that has allowed showing how the investigation in cycling equipment, fairing, position and adequate clothes of the rider is essential.

The detailed analysis of the not well-known sidewind effects on the cycling race and the study of the saved power by each rider when cycling in compact group have shown a remarkable interest. It has been pointed out the significant breaking effect of the lateral wind on the riders and how the artificial tailwind that a group creates at moderate speed, constitutes a powerful help in high competition races or in simple recreational trips like many groups of amateur cyclists around the world do every week-end.

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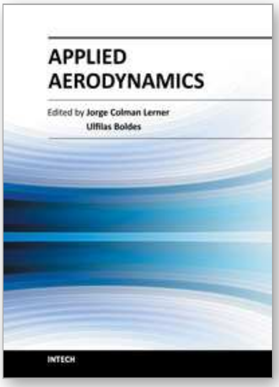


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Aerodynamics, from a modern point of view, is a branch of physics that study physical laws and their applications, regarding the displacement of a body into a fluid, such concept could be applied to any body moving in a fluid at rest or any fluid moving around a body at rest. This Book covers a small part of the numerous cases of stationary and non stationary aerodynamics; wave generation and propagation; wind energy; flow control techniques and, also, sports aerodynamics. It's not an undergraduate text but is thought to be useful for those teachers and/or researchers which work in the several branches of applied aerodynamics and/or applied fluid dynamics, from experiments procedures to computational methods.