Helge Nørstrud
Editor

International Centre for Mechanical Sciences

Sport Aerodynamics

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SPORT AERODYNAMICS

EDITED BY

HELGE NØRSTRUD

NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY
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PREFACE

Sport aerodynamics constitutes the science of aerodynamics coupled to the human activity of sports, i.e. the biomechanics of the human body under the influence of aerodynamic forces. It also encompasses the use of various equipments (or aids) in performing the individual sport activity. The aerodynamic interaction often implies the task to minimize a drag force which must be overcome by the human power output or a gravity force acting on the body. In the areas of, say, soccer or ski jumping the lift force also plays an important role. Bicycling is a further example where sport equipment is essential in performing the art of exposing the human body to the air environment. Hence, three fundamental areas of subjects will be covered in the book such as

A. *Basic aerodynamics (lift, drag, friction etc.)*
B. *Basic biomechanics (sport medicine, performance analysis etc.)*
C. *Sport equipment design (suits, helmets, shoes etc.)*

In order to pay attention to the environmental influence of the individual sport activities, the book will be divided in the following subdivisions:

- *Track running (human power, heat balance)*
- *Ice skating (suits, medical issues)*
- *Cross-country skiing (flat terrain, uphill, downhill)*
- *Ball aerodynamics (tennis, soccer, golf, cricket and baseballs)*
- *Ski jumping (suits, ski equipment)*
- *Downhill and speed skiing (terminal velocity)*
- *Bicycling (equipment, group cycling)*

The underlying physical phenomena of the sport activities listed above will be throughly discussed together with the basic equations and the physical quantities involved. Since the theme "Sport Aerodynamic" spans a wide variety of fluid mechanical and biomechanical disciplines, extensive theoretical exposition will be limited. However, many examples will be given with numerical solutions. The reader will also be guided into the literature which exists for the various topics discussed, so she or he can go into a deeper study of the particular sport activity at wish.

Helge Nørstrud

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Basic Aerodynamics

Helge Nørstrud
Department of Energy and Process Engineering,
Norwegian University of Science and Technology,
Trondheim, Norway

1 Introduction

Aerodynamics is basicly the pressure interaction between a body and the surrounding air, see Figure 1. The body can be stationary in a flowfield, i.e. in a windtunnel (Figure 2) or the body moves in still or unsteady air (Figure 3). In sport aerodynamics the athlete will encounter various forces and a graphical overview is given in Figure 4.

Figure 1. The megaliner Airbus A 380 (Photo: Airbus).

To analyse an athlete and/or his equipment in performing the sport activity under consideration we have three methods at hand, i.e. either to make an experimental test or to perform a theory and finally to adopt the computer for solving the underlying equations, see Figure 5.

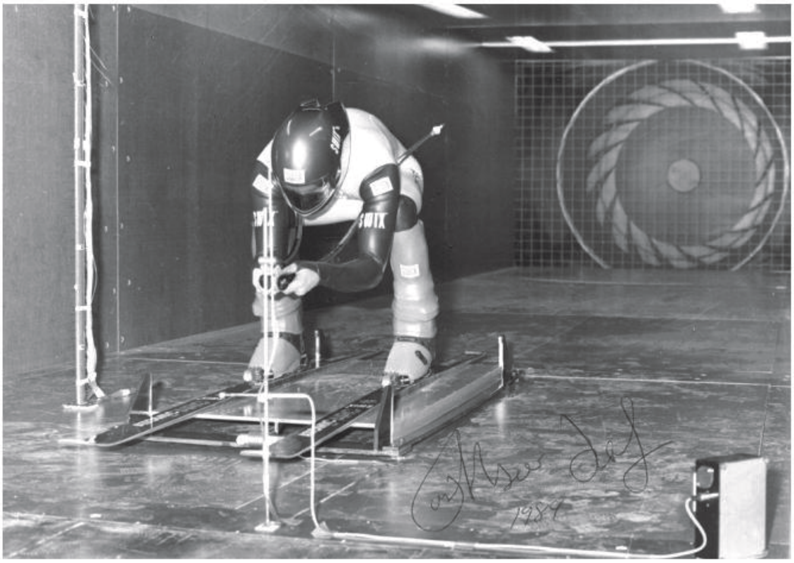

Figure 2. A speed-skier in a windtunnel at sea level measures a drag area of 0.13 m^2 and will experience a wind force of 6.26 kg at a windspeed of 100 km/h (gale/storm on the Beaufort scale). If the skier stands in an upright position the drag area will be 5 times larger and, hence, the wind force will be 31.3 kg (Photo: NTNU).

Figure 3. Ingard Strand (NOR) jumps from Strandkolvet in Norway (1300 m altitude) and reaches a velocity of 200 km/h (Photo: Magnus Knutsen Bjørke).

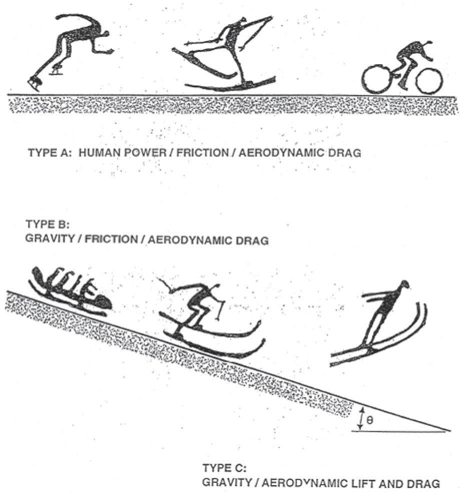

Figure 4. Sport aerodynamics and the forces involved.

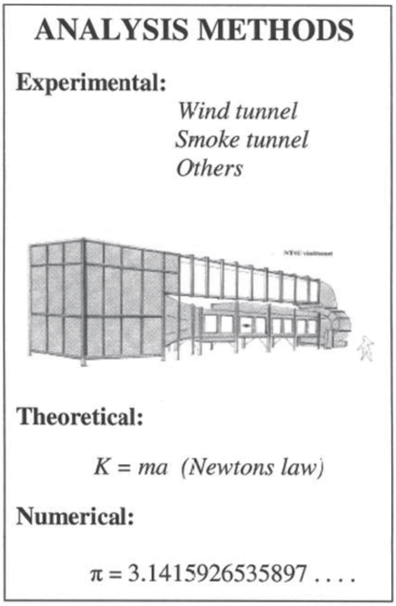

Figure 5. The three basic methods of analysis in aerodynamics.

2 Fundamental definitions

In integrating (or summing up) the steady and static pressure field p [Pa] $= p(x, y, z)$ over the body under investigation we will obtain the resulting aerodynamic force acting on the body. This force will be divided into two components, i.e. firstly the drag force D [N] acting parallell to the free stream velocity (e.g. the wind tunnel velocity) or the velocity of the body. The other component is the lift force L [N] acting normal to the drag force and these components are expressed as

$$D = \frac{1}{2}\rho_\infty C_D A U^2 \tag{1}$$

and

$$L = \frac{1}{2}\rho_\infty C_L A U^2 \tag{2}$$

Here ρ_∞ [kg/m^3] denotes the air density in the free stream, A [m^2] is a reference area and U [m/s] is the velocity in the wind tunnel or of the body. The two dimensional coefficients $C_D[-]$ and $C_L[-]$ are respectively the drag coefficient and the lift coefficient. The reference area A is the frontal area of the body in the case of drag evaluation, but for lifting bodies (like an airplane) the reference area is the lifting area (or the wing area for an airplane). The product $C_D A$ [m^2] is referred to as the drag area and is an indirect measure of the drag D, see also Figure 2. Since A is a fixed geometric value the coefficient C_D plays an important role in reducing the drag. Some values for C_D with reference to the frontal area are given in Figure 6.

Another dimensionless coefficient often used is the pressure coefficient $C_p[-]$ defined as

$$C_p = (p - p_\infty)/q_\infty \tag{3}$$

Here the lower index ∞ refers to the free stream and $q_\infty = 1/2\rho_\infty U_\infty^2$ is the dynamic pressure. The static pressure p acts normal to the body surface and gives rise to the socalled pressure drag on the body. The shear stress tangential to the body surface is responsible for the viscous drag.

Induced drag denotes the third part of the total drag and is related to the lift produced by a body, see Figure 7.

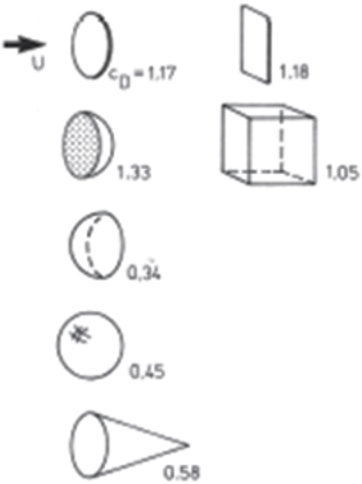

Figure 6. Drag coefficient for various bodies.

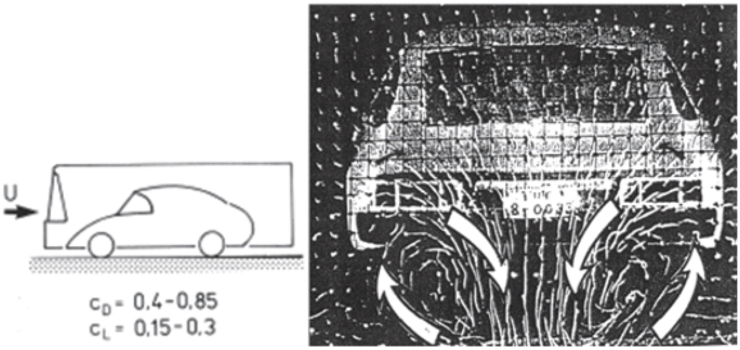

Figure 7. Vortical flow behind a lifting car (Photo: Unknown).

A body (like a car, an airplane or a ski jumper) generates lift due to the pressure differences above and under the body and trailing vortices will appear in the wake. This is visualized with a flow screen in a wind tunnel (Figure 7).

3 Similarity parameters

The most important dimensionless parameter in aerodynamics is the Reynolds number $Re[-]$ defined as

$$Re_\ell = U\ell/\nu \tag{4}$$

and describes the ratio between the inertia force and the viscous force. Here U is the flow velocity, ℓ [m] is a characteristic length and ν [m^2/s] is the kinematic viscosity which for air is equal to the value 0.000015. The critical Reynolds number designates a value where e.g. the drag of a body changes very rapidly.

Another similarity parameter is the Mach number $M[-]$ which is the ratio between the local flow velocity u [m/s] and the speed of sound c [m/s], i.e.

$$M = u/c \tag{5}$$

For $M < 0.3$ the flow can be regarded as incompressible and at a velocity of $u = 70$ m/s ($= 252$ km/h) at sea level, where $c = 343$ m/s; the Mach number will be $M = 0.2$.

4 The earth atmosphere

Since air is the key medium in sport aerodynamics we will introduce the following picture of Mount Everest (see Figure 8).

The atmospheric data below shows the air pressure and density from sea level up to the altitude of $z = 9000$ m.

It is convenient to adopt the approximation for an isothermal atmosphere, i.e.

$$\rho(z) = \rho_0 \exp(-\beta z) \tag{6}$$

where the air density $\rho(z)$ is defined through the value at sea level $\rho_0 = 1.225$ kg/m^3, the altitude z [m] and the scaling factor $\beta = 0.0001064$ m^{-1}.

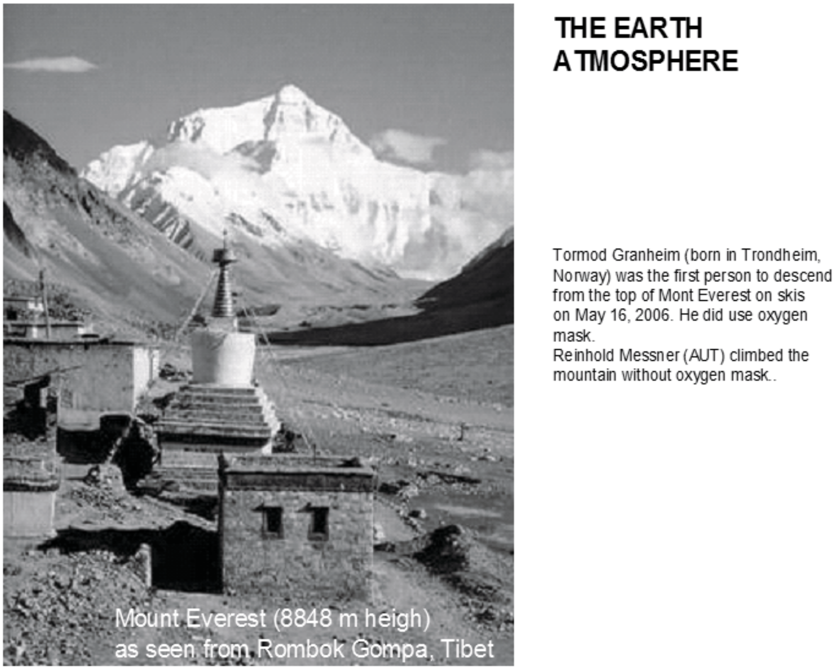

Figure 8. Mount Everest (Photo: Internet).

Table 1. Meteorological data taken from the U.S. Standard Atmosphere, 1962.

GEOMETRIC ALTITUDE, z [m]	AIR PRESSURE, p[mb]	PRESSURE RATIO, $p/p_0[-]$	**AIR DENSITY,** ρ **[kg/m^3]**	DENSITY RATIO, $\rho/\rho_0[-]$
0	1013.25	1.0	**1.2250**	1.0
200	989.45	0.977	**1.2017**	0.981
400	966.11	0.953	**1.1786**	0.962
600	943.22	0.931	**1.1560**	0.944
800	920.78	0.909	**1.1337**	0.925
1000	898.76	0.887	**1.1117**	0.907
3000	701.21	0.692	**0.9093**	0.742
5000	540.48	0.533	**0.7364**	0.601
7000	411.05	0.406	**0.5900**	0.482
9000	308.01	0.304	**0.4671**	0.381

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Factors influencing on running

Lars Sætran
Norwegian University of Science and Technology N-7491 Trondheim, Norway

1 VO2max

Running economy is important, but can it be altered? It seems that persons beginning exercise definitely become more efficient with training, as do persons who are already trained but who continue heavy training. Conley et al. (1981) followed a single runner during 6 months of interval training and found that the subject's running efficiency improved by between 9 and 16% at three different speeds. However, his body weight also fell about 6%, which could have been the more important factor explaining the improved running efficiency. Subsequently these authors showed that the running efficiency of Steve Scott, Americas premier 1500 m runner of the early 1980s, improved with interval running. Svedenhaug and Sjodin (1985) showed that the running efficiencies of a group of elite Swedish distance runners improved between 1 and 4% during the course of one year, changes that where in the range of those measured in the adolescent runners is studied by Daniels and Oldridge (1971). Svedhaug and Sjodin speculated that the continual improvements in the running performances of these Swedish athletes were due to slowly progressive improvements in their running efficiencies rather than to increase in the VO2max values, which were relatively fixed, increasing only during that phase of the season when the athletes were performing high-intensity interval-type training.

Athletes appear to choose stride lengths at which they are most efficient, that is, at which oxygen uptake is the least (Cavanagh and Williams 1982). When forced to take either shorter or longer strides but to maintain the same running pace, athletes become less efficient and require an increased oxygen uptake. With training, runners increase the length of their strides and reduce their stride frequency (Nelson and Gregor 1976). Some researchers believe that this optimises running efficiency because increasing stride length is more economical than increasing stride frequency.

Although VO2max values differ between the sexes, gender has no effects on running efficiency, trained men and women are equally efficient

(Maughan and Leiper 1983). Race may influence running efficiency, researchers have found that Asians and Africans utilise 17% less energy than Europeans when lying, sitting, or standing, but no studies have compared energy uses of these groups during exercise. In a study of elite runners of different racial groups, researchers found no race-related differences in running economies (Noakes 1991).

2 Extra weight

Clothing weight is another factor that can influence an athletes efficiency. Stevens (1983) calculated the effect of the weight of clothing on marathon racing performance. He found that the typical nylon vest and shorts worn by marathon runners weighted 150 g, 100% cotton shorts and vest weighted 234 g, and the heavy tracksuits weighted 985 g. Stevens calculated that changing from nylon to cotton clothing would increase a world-class runners marathon time by about 13 seconds and an average 3:40 marathoners time by about 23 seconds. Running in a full tracksuit should increase the average runners marathon time by about four minutes.

However, laboratory experiments do not necessarily substantiate these calculations. Cureton et al (1978) found that the addition of up to 5% of body weight to the torso increased the oxygen cost of running by only about 2.5%. Extrapolation these data suggest that the addition of even 1 kg of extra weight to the torso in the form of clothing would increase the oxygen cost of running by less than 0.5

Extra weights added to their legs or feet appear to have a far greater effect on the running economy.Martin (1985) found that the addition of 0.5 kg to each thigh or to each foot increased the oxygen cost of running by 3.5 and 7.2%, respectively, values considerably higher than those found by Cureton et al (1978). A number of other studies show that the addition of 1 kg to the feet increases the oxygen cost of running by between 6 and 10%, or about 1% per 100 g increase in the weight of footwear. The increase is the same in men and women.

Clearly, a 1% savings in energy expenditure during a standard marathon race, for example, is not inconsiderable, if translated directly into a 1% improvement in performance it would mean a savings of 77 seconds at world-record marathon pace, equivalent to a sub 2:07 standard marathon. But we have yet to prove that these energy savings will cause an equivalent improvement in running performance.

In-shoe orthotics used in the treatment of a number of running injuries will increase shoe weight and therefore might influence running economy adversely. In the study of Burkett et al (1985), the addition to an 80-g orthotic device to each running shoe increased the oxygen cost of running by about 1.4%, smaller increases, 0.4 to 1.1%, were reported by Berg and Sady (1985). These studies indicate that the added weight of the orthotic device decreases running economy in direct proportion to its weight.

Work at the Nike Sport Research Laboratory has shown that the air pockets used in the midsole of different Nike air running shoes reduces the oxygen cost of running by 1.6 to 2.8% at a running speed of 16 km/hr. If these savings directly translate into equivalent improvements in racing performance, then they are significant, at least for the top athletes. Further research is needed to study this possibility.

3 Running surface, gradient and wind speed

Obviously, prevailing conditions such as running surface, gradient, and wind speed and direction will have considerable effects on the runners economy. The influence of the running surface on the oxygen cost of running was first noted by Passmore and Durnin (1955), who reported that the oxygen cost of walking across a plowed field was 35% greater than the cost of walking at the same speed on a smooth, firm surface. Running on sand has a similar effect (Wyngand et al 1985). McMahon and Green (1979) suggested that optimising the spring constant on a running track will likely improve running performance and running economy (and reduce injury risk).

One of the first scientists to study the influence of wind speeds on running performance was G. Pugh, whose work on the effects of altitude on athletic performance is among the classic contributions on the topic. Pugh performed four different studies designed to measure how wind speed and the gradient of the running surface influence the oxygen cost of running (Pugh 1970). His studies showed that the extra cost of running into a facing wind increased as the square of the wind speed. Thus the oxygen cost of running into a 66-km/h headwind increases by 30 ml/kg/min. Similarly, running up an 8% incline increases the oxygen cost of running by about 20 ml/kg/min.

The figure indicates that for each 1 km/hr increase in running speed, the oxygen cost increases about 4 ml/kg/min. Thus, the increased oxygen cost of 30 ml/kg/min caused by running into a 66 km/hr wind would cause a 7.5 km/hr were reduction in running speed. Similarly, an 8% gradient would slow the runner by 5 km/hr.

Pugh also showed that at the speeds at which middle-distance track events are run (6 m/s or about 67 seconds per 400 m), about 8% of the runner's energy is used in overcoming air resistance. But by running directly behind a leading runner (or drafting) at the distance of about 1 m, their

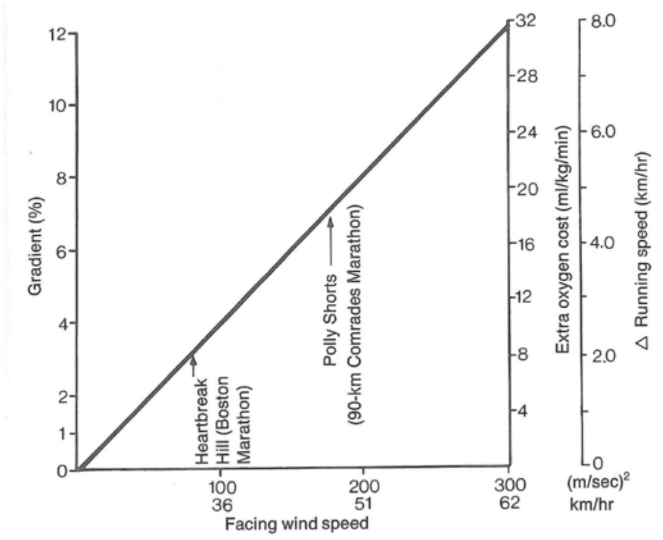

Figure 1. Extra cost of oxygen for running uphill and in a facing wind

athlete can save 80% of that energy. In a middle-distance race this would be equivalent to a savings of about 4 seconds per lap. However, Pugh considers it unlikely that in practice the following athletes would ever be able to run as close to the lead runner to benefits to this extent. By running slightly to the side of the lead runner, the following runner would probably benefit by about 1 second per lap (Pugh 1970).

Another researcher to study the benefits of drafting was C. Kyle (1979). His calculations suggest that at word-record mile pace a runner running 2 m behind the lead runner would save about 1.66 seconds per lap, which generally confirmed Pughs estimations. Kyle calculated that the benefits of drafting in cycling are much greater than in the running, some 30% or more. In addition, the larger the group and the farther from the front the cyclist rides, the more the cyclist benefits.

In contrast, the aerodynamic drag is increased when runners are positioned abreast because the larger frontal area results in a larger sheared drag (Bassett et al 1987).

These findings explain why track athletes find pacers to be such essential ingredients in aiming for world track records. In addition, these findings explain why the world records in the sprints are set at altitude. During sprinting, the energy cost of overcoming air resistance rises to between 13 and 16% of the total cost of running. Thus, the sprinter benefits greatly by running at an altitude where air resistance is considerably reduced. It is interesting that when the runner is racing on a circular track and optimum strategy is to accelerate into the wind and to decelerate when the wind is from behind, the opposite of what one would expect (Hastell 1974).

M. Davies (1980) extended Pughs findings. Davies used essentially the same techniques as Pugh but included observations on the effects of downhill running and of following winds of different speeds.

Davis found that when the runner was measured on the treadmill, facing winds of up to 18 km/hr had no effect of the oxygen cost of running, but that the same conditions on the rode will have a very marked effect. On the treadmill, the athlete does not move forward and thus does not expend energy overcoming air resistance. However, an athlete who runs on the rode into a wind of 18 km/hr faces an extra wind speed equal to that of his or her running speed plus that of the prevailing wind.

The practical relevance of this is that on a calm day, anyone running slower than 18 km/hr will not benefit by drafting in the wake of other runners. However, runners stand to gain considerably by drafting when running at faster speeds or when running into winds that, when added to the running speeds, would make the actual wind speed greater than 18 km per hour.

Of course, the world marathon record is run at a faster pace than 18 km/hr. This means that athletes intend on setting world records would be well advised to draft for as much of the race as possible. Front running in the marathon is always as wasteful of energy as is front running on the track. One can only assume that as the runners begin to realise this fact, we shall see pacesetters in marathon races just as we have them in track races.

The only way besides drafting to reduce wind resistance is to run with a following wind, the speed of which is at least equal to that of the runner. Davies calculated that under these circumstances, the removal of energy required to overcome wind resistance at world marathon pace (19.91 km/hr) would increase their running speed by about 0.82 km/hr, equivalent to a reduction in the racing time of about 5 minutes. Similarly, drafting in a tightly knit bunch for the entire race would reduce air resistance by about 80%, allowing the runner to run about 4 minutes faster.

Davies found that the effects of a tail wind on the oxygen cost of running was about half that of a facing wind. Thus, a following wind of 19.8 km/hr is of little assistance to runners running slower than 18 km/hr, but a following wind of 19.8 km/hr would assist in a world marathon record attempt to the extent of a 0.5 km/hr increase in speed. Higher following wind speeds of 35 to 66 km/hr would improve running speeds by 1.5 to 4 km/hr.

At higher facing wind speeds, the oxygen cost of running increases enormously. Wind speeds of 35 km/hr would reduce running speeds by about 2.5 km/hr, speeds of 60 km/hr by about 8 km/hr.

Finally, Davies calculated the additional oxygen cost of running uphill and the energy savings by running downhill. He found that the energy savings during downhill running equaled only half of the energy that would be lost when running on an equivalent uphill gradient. Uphill running increased the energy costs by about 2.6 ml/kg/min for each 1% increase in gradient. This is roughly equivalent to a reduction in running speed of about 0.65 km/hr. Downhill running was associated with a reduction in the oxygen cost of running by about 1.5 ml/kg/min for each 1% gradients, equivalent to an increase in speed of about 0.35 km/hr.

The practical value of this information is twofold. First, it indicates that time lost going uphill can never be fully regained by running an identical downhill gradient. Second, the data shown in Figure A can be used to estimate how much time you can expect to lose or gain on the particular section of a race (if you know the gradient of that section).

4 Aerodynamics

Kyle (1986) studied the aerodynamic drag effects of athletic clothing and showed that the following factors increased the aerodynamic drag experienced by the runner: shoes with exposed laces 0.5%hair on limbs 0.6%, long socks 0.9%, short hair 4%, loosely fitting clothing 4.2% and long hair 6%. He also calculated that by reducing aerodynamic drag as little as 2%, equivalent to a haircut, a runner would reduce his or her running time over 100 m by 0.01 seconds and in the standard marathon by 5.7 seconds. Even better results could be achieved by running in a custom-fitted speed suit with a tight-fitting hood to cover their hair and ears. Such a suit made of polyurethane-coated, stretchable nylon reduces aerodynamic drag by smoothing the airflow around the streamlined areas of the chin, ears, and hair, and by eliminating the flapping of loose clothing. Calculations suggest that wearing such clothing would reduce running time in the 100 m race by 0.284 seconds (3%) and by 1:34.50 (1%) in the standard marathon (Bassett et al 1987). Unfortunately, this clothing is impracticable for marathon runners because it's streamlining prevents heat loss. The first attempt to use the streamlined hood in Olympic relay competition had a disastrous results - the 1988 United States Olympic Games 100 m relay team was disqualified when one runner received the baton outside the legal zone because he was unable to hear the approach of the other runner!

5 Controlling body temperature

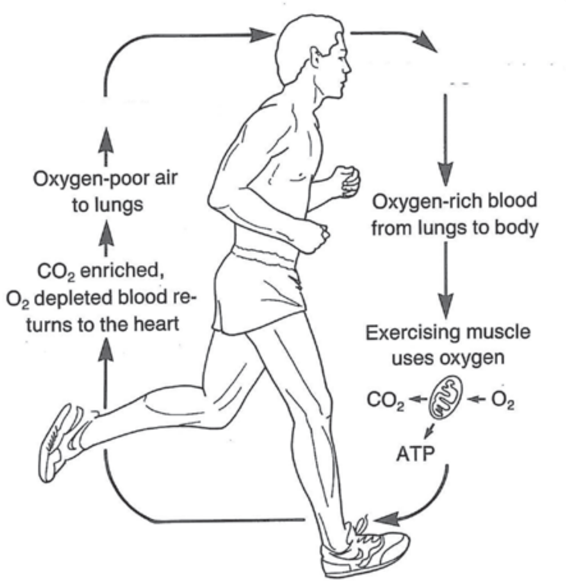

Figure 2. A runner's metabolism

A runner faces a major problem: the excess heat produced by muscle contraction. Humans are homeotherms, and to live they must keep their body temperature within a narrow range (35 to 42^{o}C) despite wide variations in environmental temperatures and differences in levels of physical activity.

During exercise the conversion of chemical energy stored in ATP (adenosine triphosphate) into mechanical energy is extremely inefficient, so that as much as 70% of the total chemical energy used during muscle contraction is released as heat rather than as athletic endeavor.

Thus, when Don Ritchie wins an ultramarathon at an average pace of 16.3 km/hr he utilises about 56 kJ of energy every minute or 18,482 kJ in the 5 1/2 hours that he runs. Of this, only 5942 kJ help transport the athlete from the start to the finish of the race, the remaining 12,540 kJ are

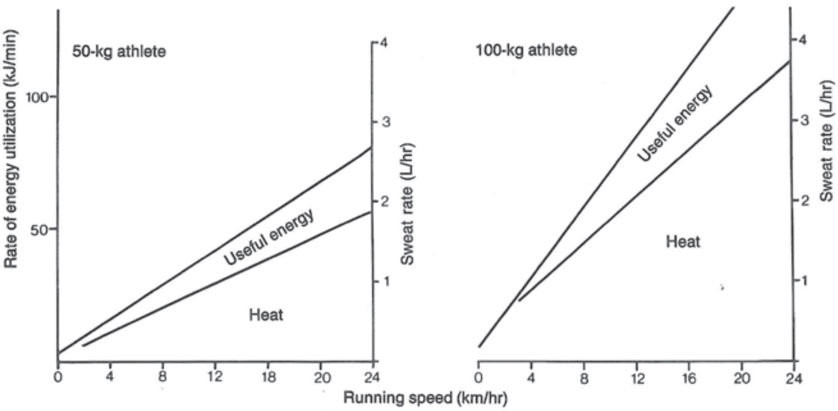

Figure 3. Energy

nothing more than a hindrance, as they serve only to heat the athlete. Were the athlete unable to lose that heat, his body temperature would rise above 43^oC, causing heatstroke.

To prevent disastrous overheating and heatstroke and to control the increased heat associated with exercise, the body must be able to call upon and number of very effective heat-losing mechanisms.

6 Mechanisms for heat loss during exercise

As exercise begin, the blood flow to the muscles increases. Not only does the heart pump more blood, but blood is preferentially diverted away from nonessential organs and toward the working muscles and skin. As blood passes through the muscles, it is heated, and it distributes the added heat throughout the body, particularly to the skin. In this manner, as well as by direct transfer from muscles lying close to the skin, heat is conducted to the skin surface. Here, circulating air currents convect this heat away, and any nearby objects whose surface temperature is lower than the skin temperature attract this heat, which travels by electromagnetic waves in the form of energy transfer known as a radiation.

In another method of heat loss, surface heat evaporates the sweat produced by the sweat glands in the skin. Sweating itself does not lose heat,

heat is lost only when the sweat actually evaporates. The efficiencies of all these mechanisms depend on a variety of factors, most of which are open to modification by the athlete.

7 The exercise intensity

As the intensity of exercise increases, the body must decide whether to pump more blood to the muscles to maintain their increased energy requirements or to assist heat dissipation by increasing the skin blood flow. Faced with conflicting demands, the body always favors an increased blood flow to the muscles. The result is that while body heat production is increased, the ability to lose that heat is decreased.

It appears that athletes running at word-record speeds, at least in races up to 16 km, develop marked limitations to skin blood flow and therefore have limited abilities to lose heat. They thus run in micro-environments in which their abilities to maintain heat equilibrium depend entirely on the prevailing environmental conditions (Pugh 1972). If these conditions are unfavourable, the athletes will continually accumulate heat until their body temperatures reach the critical level at which heatstroke occurs. Two famous athletes running at word-record pace who developed heatstroke when forced to race in unfavourable environmental conditions were Jim Peters in the 1964 Empire Games Marathon and Alberto Salazar in the 1980 Falmouth 12 km Road Race.

8 Environmental factors affecting heat loss

The air temperature and wind speed determine the amount of heat that can be lost from the skin by convection, which is the heating of the surrounding air by the skin.

High facing-wind speeds cause a large volume of unwarmed air to cross the skin in unit time and therefore allow for greater heat loss by convection. Running itself produces an effective wind speed that aids convective heat loss but may not be sufficient to increase heat loss adequately in severe environmental conditions. Obviously, a wind coming from behind the runner at the same speed that the runner is moving forward will cause him or her to run into a totally windless environment, which will prevent convective heat loss. In contrast, the wind speed developed by cyclists appear to be sufficient to compensate even for severe conditions, which explains why heat is not as great a problem for endurance cyclists as it is for runners.

At rest the body skin temperature is about 33^{o}C. If you exercise in environmental temperatures greater than 33^{o}C, heat cannot be lost by convection, because the air temperature is higher than that of the body surface. In this case the direction of heat transfer is reversed, and the superficial tissue gain heat from the environment. In these conditions, the only avenue for heat loss is by sweating. Sweating removes 1092 to 2520 kJ of heat per litre of sweat evaporated depending on whether the sweat evaporates or, as usually happens, a large percentage drips from the body without evaporating. As the air humidity increases, the bodys ability to lose heat by this mechanism decreases.

The body can absorb additional heat from the environment, in particular from the sun. The body temperature is cooler than that of the sun, thus the body will absorb radiant energy from the sun. Obviously, the amount of radiant energy to which the athlete is exposed is greater when there is no cloud cover and least when cloud cover is absolute.

These three environmental factors that determine the athlete's ability to lose heat - wind speed, the humidity and temperature of the air, and the radiant energy load - are measured in the wet bulb globe temperature (WBGT) index.

The WBGT index integrates the measurement of radiant energy (as the temperature of a black globe - the globe temperature) with the wet bulb temperature (measured by the thermometer covered by a wick permeated by water). The difference between the wet bulb temperature and the prevailing air (dry bulb) temperature is a measure of the humidity of the air and therefore is also a measure of the ease with which sweat will evaporate from the athlete. Furthermore, wind blowing over the wet wick of the wet bulb thermometer will increase the rate of evaporate cooling and the therefore lower the wet bulb temperature. In this way, the prevailing wind speed also influences the WBGT.

9 Dehydration

With sweating, fluid is removed from the body causing dehydration, which may be compounded by vomiting and diarrhea. Whyndham and Strydom (1969) drew attention to what they believed to be the dangers of dehydration in predisposing the athletes to heatstroke. They studied runners in a 32 km road race and showed that the body temperature of athletes who became dehydrated by more than 3% of their body weight approached values previously recorded only in victims of heatstroke. In addition, they found that athletes weighing 70 kg or more who had not drunk during the race incurred 5% water deficits and had markedly elevated body temperatures after the race.

The conclusion that these authors drew is now believed to be incorrect

(Noakes 1991). In particular, it seems that dehydration is not the most important factor determining the body temperature during exercise. Nevertheless, the findings of Whyndham and Strydom (1969) drew attention to the potential dangers of the International Amateur Athletic Federation rule number 165:5, which stipulated that marathon runners could not drink fluids before the 11th kilometre mark of the standard marathon and thereafter could drink only every 5 km. This ruling discouraged marathon runners from drinking during races and promoted the idea that drinking during running was unnecessary and a sign of weakness. This rule was eventually repealed.

That early marathon runners were not used to drinking fluids regularly during races is shown by the trivial amounts drunk by Athur Newton during his races. Jim Peters (1957) described the conventional wisdom in the following statement about marathon racing:

There is no need to take any solid food at all and every effort should also be made to do without liquid, as the moment food or drink is taken, the body has to start dealing with the digestion and in so doing some discomfort will almost invariably be felt.

Although dehydration is not the critical factor predisposing athletes to heatstroke during exercise, marked dehydration does have detrimental effects. Skin blood flow is reduced, and body heat storage (and therefore body temperature) is increased by dehydration. However, the effects are somewhat less dramatic than generally believed (Noakes 1991).

10 Clothing

Apart from aesthetic reasons, the reason for wearing clothing is to trap a thin layer of air next to the body. Because air is a poor conductor of heat, this thin layer rapidly heats to body temperature and act as an insulator preventing heat loss. Clearly, any clothing that is worn during exercise in the heat must be designed for the opposite effect - to promote heat loss.

Marathon runners have learned that the light, porous clothing such as fish net vests best achieve this heat loss. In contrast, T-shirts or heavy sweatsuits, particularly when soggy with sweat, become very good insulators, preventing adequate heat loss.

Novice runners, particularly those who might consider themselves overweight, often train in full tracksuits in the heat. Many neophyte athletes probably believe that the more they sweat, the harder they must be exercising and therefore the greater the weight they stand to lose. The unfortunate truth is that in running, the energy cost is related only to the distance run. Thus, to lose more weight, one needs to run a greater distance.

Excessive sweating will effect a sudden loss of weight by dehydrating the body, this is the procedure used by boxers, jockeys, and wrestlers in making the weight. By exercising in the heat for as little as half an hour, one can lose as much as 1 kg, but this is a fluid loss that will be rapidly replaced if the athlete rehydrates by drinking. In contrast, to lose a real kilogram of body weight one must expend about 37500 kJ of energy, equivalent to running about 160 km.

A runner who lives in a moderate climate seldom (if ever) needs to train for any period in a track suit. By doing so, the runner merely increases discomfort and promotes conditions favourable for heatstroke.

11 Heat acclimatization

When athletes who have trained exclusively in cool weather are suddenly confronted with hot, humid conditions, they suffer immediate and dramatic impairments in performance. However, with perseverance and continued training in the heat, performance soon improves, returning to normal within a short period.

The process underlying this adaptation is termed Heat Acclimatization. It begins after the first exposure to exercise in the heat, progress is rapid, and is fully developed after 7 to 10 days. Only by exercising in the heat can one become acclimatized to the heat. The optimum method for achieving this is to train daily in the heat for periods of 2 to 4 hours for 10 days. Once established, heat acclimatization is fully retained for about two weeks. Thereafter, it is lost at rates that vary among individuals. It is best retained by those who stay in good physical condition and who re-expose themselves to exercise in the heat at least every two weeks.

Important changes occur with heat acclimatization: Heart rate, body temperature, and sweat salt (sodium chloride) content during exercise decreases, whereas sweating rate increases due to increased secretory capacity of the sweat glands. In addition, metabolic rates and the rate of muscle and blood lactate accumulation are decreased by heat acclimatization (Young et al 1985), as is the rate of muscle glycogen utilisation.

Heat acclimatization confers considerable protection from heat injury. Equally important, in competition in the heat, the heat-acclimatized athlete will always have the edge over an equally fit, but unacclimatized opponent.

12 Sponging

As the skin temperature rises, it causes blood to pool in the veins of the arms and legs. This is because the elevated skin temperature paralyses the veins, which dilate and soon fill with a large volume of blood.

This blood is effectively lost from the circulation and can only be returned to the circulation if the skin temperature is again lowered. This can be achieved by Sponging (this is literally wetting the skin with a sponge).

A recent study confirmed that wetting the skin did indeed lower the skin temperature during exercise but did not aid heat loss (Bassett et al 1987). Thus the benefits of sponging during exercise probably relate to its effect on the central circulation.

13 Factors explaining impaired running performance in the heat

Anyone who has to run a marathon or longer race in the heat knows that such races are much more difficult than are races of the same distance run in cool conditions. The most likely explanation for this comes from recent studies showing that pre-cooling of the body or of the active muscles either prior to or during exercise prolongs endurance time to exhaustion in both dogs and humans (Kozlowski et al 1985). This cooling keeps the muscle temperature lower during subsequent exercise and alters the metabolic response by decreasing the rate of muscle glycogen utilisation, muscle lactate accumulation, and the fall in muscle high-energy phosphate contents, thereby allowing the cooler muscle to exercise for longer. By inference we may conclude that the sustained elevation of muscle temperature that occurs during prolonged exercise may be one of the most important factors limiting endurance performance.

14 Calculating sweat rate during exercise

To calculate your sweat rate or to figure how much your current drinking pattern during races falls short of replacing your sweat losses, you could try the following experiment.

Weigh yourself (naked) on the scale reading in kilograms, immediately before (WB) and immediately after (WA) a run in conditions and at a race pace to which you are accustomed. Measure carefully the total amount of fluid (F) in litres that you ingest while running. You can then calculate your sweat rate fairly accurately.

$$SweatRate\,(L/hr) = \frac{(WB - WA) + F}{RunningTime(hours)} \qquad (1)$$

Your fluid replacement will have been adequate if, after races longer than 30 km, you have lost less than 2 to 3 kg and are not dehydrated by more than 3%, calculated by this equation:

$$Dehydration\,(\%) = \frac{WB - WA}{WB} x100 \qquad (2)$$

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Cycling Aerodynamics

Giuseppe Gibertini and Donato Grassi
Dipartimento di Ingegneria Aerospaziale, Politecnico di Milano, Milano, Italy

Abstract A general introduction presents the main concepts about biker and bicycle aerodynamics. A decription of the drag reduction problem is presented and the athlete position effects as well as the main bicycle components effects are examinated. Advices are proposed to improve performances (taking the international regulations as a constant reference).

1 Introduction

In the present treatise, among the severall possible items related to cycling and wind, the resistance to the bicycle and biker progression due to the relative wind (produced by the motion itself) will be the focal point.

Other possible items related to aerodynamics could be the effects of natural wind (cross-wind, favourable or contrary wind) as well as ventilation problems (see, for example, Bruühwiler et al. (2004). Among these, only cross-wind effects will be briefly described.

Aerodynamic resistance is a non negligible topic for many kind of bicycle competitions but it is the fundamental problem when the velocity is particularly high as in time trial competitions. For this reason the present treatise is focalized on time trial competitions.

2 The UCI regulations

The problem of bicycle aerodynamics is very complex as a great number of variables should be considered. In order to limit the degrees of freedom of the problem, only the solutions that comply the regulations of the Union Cyclist Interanationale (UCI) will be taken in account.

In the following some articles of the UCI Cycling Regulations (UCI, 2007) particularly related to aerodynamics argument will be cited and commented.

The article 1.3.006 says: 'The bicycle is a vehicle with two wheels of equal diameter. [...]'. This definitively excludes same exotic aero-bike (see for example Kyle (1991c) with the front wheel smaller than the rear one.

The article 1.3.013 says: ‘The peak of the saddle shall be a minimum of 5 *cm* to the rear of a vertical plane passing through the bottom bracket spindle. [...]’.

The article 1.3.022 says (the reference to specific diagrams are skipped in the following citation) : ‘In competitions other than those covered by article 1.3.023, only the traditional type of handlebars may be used. The point of support for the hand must be positioned in the area defined as follows: above, by the horizontal plane of the point of support of the saddle [...]’. While the article 1.3.023 says: ‘For road time trial competitions [...] an extension may be added to the steering system. The distance between the vertical line passing through the bottom bracket axle and the extremity of the handlebar may not exceed 75 *cm* [...]’. It’s important to outline, as done by UCI in a recent official dispatch, that the general indications of article 1.3.022 apply for time trial competitions too, except for what explicetely modified by the article 1.3.023, thus the upper limit for the handlebars position is the same for all the competitions. As it will be explained in the following, all together these three articles (1.3.013, 1.3.022 and 1.3.023) prohibit extreme positions, like Obree’s or ‘superman’ position, but allow for a quite aerodynamic arrangement (the so called ‘time trial position’) that, if accurately adjusted for each specific biker, leads to very good results in term of aerodynamic resistance (very close to the values obtainable with extreme positions).

3 The air resistance

The bicycle belongs to the group of vehicles that live the athlete body exposed to the wind. Furthermore the bike surface is rather small with respect to the biker surface and therefore the main part of the aerodynamic force acts on the athlete body whose position is, nevertheless, strongly related to the shape and the dimensions of the bicycle itself.

On the aerodynamic point of view the biker can be regarded as ‘bluff body’ and, generally speacking, the bike too can be considered bluff. The bluffness leads to the fact that the aerodynamic resistance is mainly pressure drag (instead of friction drag) and thus, on a very general point of view, it’s more important to reduce the frontal area than to reduce the wet area. An other general consideration is: as lift (positive or negative) is not required, it’s better to keep it as small as possible in order to avoid the production of induced drag.

Aerodynamic drag is essentially proportional to the square of the speed.

Usually it is expressed as:

$$D = \frac{1}{2}\rho V^2 S C_D \qquad (1)$$

where S is a reference surface (usually, for bluff bodies, it's the projected frontal area) and C_D is the dimensionless drag coefficient. In aerodynamics drag is defined as the projection of the aerodynamic force along the direction of the relative wind. This means that if the relative wind is aligned with the bike (no matter if it's due to bike motion only or to natural wind too) the drag coincides with the aerodynamic force opposite to the bike motion (let's call it F_x) but in case of lateral wind the two concepts are not the same.

As the present treatise is essentially focalized on what produces resistance to the motion and adsorbs power from the biker, the F_x forced will usually be considered in the following (and therefore the C_x coeffcient) although sometime the term drag will be used for brevity when no risk of ambiguity is present.

For a certain bike and biker (in a specific position) the C_x coefficient is essentially a constant as it varies slightly with the velocity (with the Reynolds number to be more correct), thus aerodynamic resistance is essentially proportional to the square of the velocity and its importance grows more and more as the velocity increases. For this reason the drag reduction is very important in time trial races were the velocity is in the order of 14 m/s (about 50 km/h) and aerodynamic resistance is more than 90% of the total resistance. Following Kyle (1989) this can easily be estimated by the following equation:

$$R = gm(C_{rr_1} + C_{rr_2}V) + \frac{1}{2}\rho V^2 S C_x \qquad (2)$$

where R is the total resistance, gm is the weight of rider and bike, C_{rr_1} is the static rolling resistance coefficient, C_{rr_2} is the dynamic rolling resistance (including wheel bearing losses and dynamic tire losses).

Typical values for the rolling resistance coefficients are $C_{rr_1} = 0.0023$ and $C_{rr_2} = 0.115 \times 10^{-4}$ s/m, while a mass of 75 kg and a drag area $SC_x = 0.24$ m^2 can be representative for a time trial biker.

With this values and a velocity of 50 km/h, corresponding to 13.89 m/s, a rolling resistance of 1.8 N is obtained and an aerodynamic resistance of 26.6 N that's the 94% of the total.

As already said, on the point of view of its aerodynamic drag the biker-bicycle system can be considered as a bluff body: the rider is rather obviously a bluff body but the bicycle too is essentially a non streamlined object except for some detail. In any case the athlete drag is more important of the bike drag (in the order of two thirds of the total amount (Kyle, 1989)), thus the biker position is the focus point for performances improving. Nevertheless, for extreme competitions, also a few percents of drag reduction can make the difference thus a good design of bike components can be important as well as helmet and dress choose.

Following Kyle (1989) it's possible to have an estimation of the time reduction due to the drag reduction in a time trial competition. The basic idea is to evaluate a typical value for the biker power simply multiplying a typical resistance for a typical mean velocity and keep the same power value to estimate a new mean velocity (and therefore a new time) with a different aerodynamic resistance. In the Table 1 the time reduction for some values of SC_x reduction are listed for three different race lenghts. The reference times and the biker powers for the three race lenghts (1 km, 4 km and 40 km) are computed on the base of resonable velocities: 57 km/h, 50 km/h and 48 km/h respectively. The table shows that also a small drag reduction can produce appreciable results. Of course this is a very rough model of the realty but neverless it gives an idea of the order of magnitude of the time gain.

Table 1. Time trial race time reduction due to drag reduction.

SC_x reduction $[m^2]$	Time reduction for 1 km race $[s]$	Time reduction for 4 km race $[s]$	Time reduction for 40 km race $[s]$
0.001	0.09	0.39	4.07
0.005	0.43	1.97	20.4
0.01	0.87	3.96	41.2
0.02	1.77	8.04	83.6

Aerodynamics is governed by non linear equation thus effects summation is not rigorously applicable. Nevertheless there is a need of separate the different effects in order to understand the main phenomena and in order to guide the optimization. For this reasons, althought it's not completely correct, the different part effects will be presented separately in the following.

4 Wind tunnel testing

The main way to study the cycling aerodynamic is the experimental testing in wind tunnel. A possible alternative to wind tunnel tests could be mea-

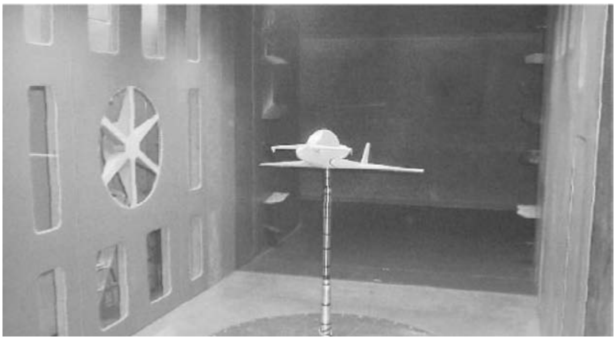

Figure 1. The GVPM aeronautical test section

surements in field conditions (as explained, for example, in Martin et al. (2006) or in the work of Grappe et al. (1997)) but, generally, the wind tunnel tests are more repetible and documentable.

In order to perform full-scale wind tunnel tests (allowing to involve the real athletes) large facilities are necessary. In fact it is well known (see for example Barlow et al. (1999)) that, in order to have realistic test conditions, the solid blockage, i.e. the ratio between the projected frontal area of the bicycle and biker combination and the sectional area of the test room should be lower than 10% (lower than 5% it'd be much better).

4.1 The large wind tunnel of Politecnico di Milano

The wind tunnel of Politecnico di Milano (GVPM) is a low speed large facility. Due to its size and its adjustable flow velocity , the aeronautical test section (see Figure 1 and Table 2) is well suitable for full scale testing in the field of sport research (for cycling, sled, etc.).

Table 2. GVPM aeronautical test section main data

Width	Height	Min velocity	Max velocity	Turbulence
4.02 m	3.84 m	10 km/h	200 km/h	$< 0.1\%$

The facility is equipped with a special roller system allows to make both the wheels spinning. A turning table on the floor allows for yawed conditions and therefore for cross flow cycling conditions. The tests are usually