Cycling Aerodynamics

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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:

$$D = \frac{1}{2}\rho V^2 S C_D \tag{1}$$

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:

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

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-

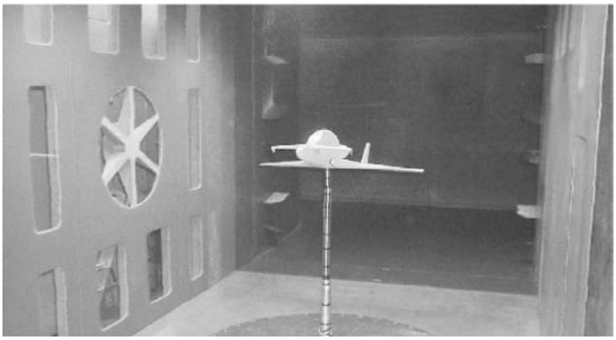


Figure 1. The GVPM aeronautical test section

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 carried out with the real athletes inside the test room although this leads to a problem of test repeatibility and long and repeated measurements are necessary to get reliable results (Flanagan, 1996).

5 The rider

As said before, the biker body drag is dominant to the other effects (it was found by Kyle and Burke (1984) that the biker drag is about from 60% to 70% of the total amount).

As a matter of fact, the attribution of a percent quota of drag to the bike and the biker could be considered contestable, as the two effects cannot be really decoupled, and it's here considered nothing more than an indication.

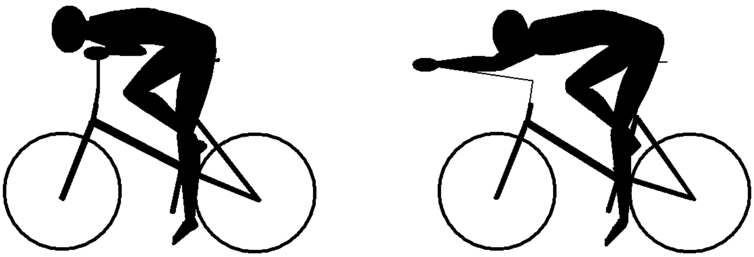
The fact that the biker drag is the most part of the total drag is rather easily inferred if the body surface is compared with the bike one, both in terms of projected frontal area and in terms of wet area. Of course, as the human position is the focus, the bicycle dimensions (frame and handler dimensions) have to be considered as they strongly influence the biker body attitude: as a matter of fact, the bicycle is a very rigid constrain to the rider position and several strange bicycles have been developed in the past in order to keep the rider in a very aerodynamic position. Of course these new solutions have to take in account the roles specific of the considered competition.

5.1 The biker positions

Generally speaking the main way to reduce the drag is the reduction of the projected frontal area and this is essentially obtained keeping the body aligned with the wind as more as possible. That's the reason why, in the recent past, very good performances have been obtained with rather extreme positions with the biker body highly stretched forward with horizontal torso. Depending on the arms attitude these extreme biker positions can be essentially divided in two typologies: the first is the Obree's position with the arms drawn up below the chest; the second is the superman position with the arms stretched straight forward (Kyle and Weaver, 2004) as sketched in Figure 2.

Both these positions produce a large drag reduction, up to 30%, respect to the standard (drops) position (Bassett et al., 1999; Lukes et al., 2005).

But UCI decided to stop this rush to exotic solutions (see, for example, Broker et al. (1997)) fixing strict constraints to the bike shape in order to go back to more traditional cycling (as told before, it's the bike that mainly determines the biker position) and so both Obree's and superman position



The Obree's position. The superman position.

Figure 2. The extreme aero-positions.

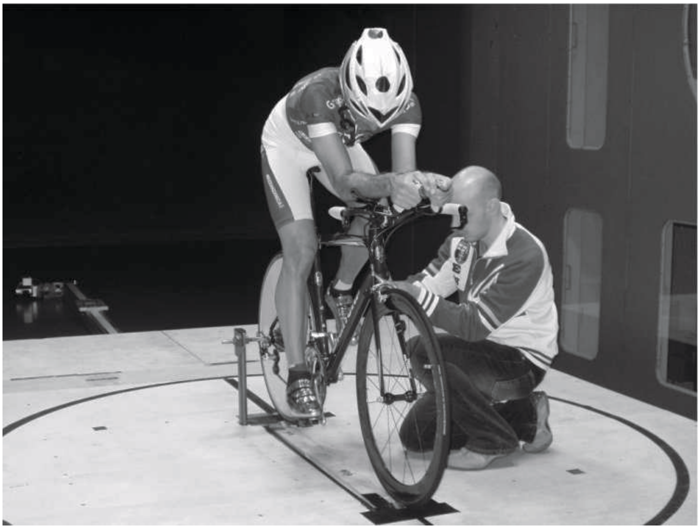
are now banned. In fact, the Obree's position needs to raise the handlebars more than permitted by article 1.3.022 (see Section 2 on UCI regulations) and the superman position requires to protrude forward the hands more than permitted by article 1.3.023 (see again Section 2).

Two series of systematic tests have been carried out in GVPM facility, in order to evaluate the biker position effect. The first series of tests was carried out on January 2007 (Gibertini et al. (2008)) with a 1.75m tall man (in the following he's called "biker A") while the second tests series was carried out one year later (january 2008) with a taller 1.8m athlete (Biker B)

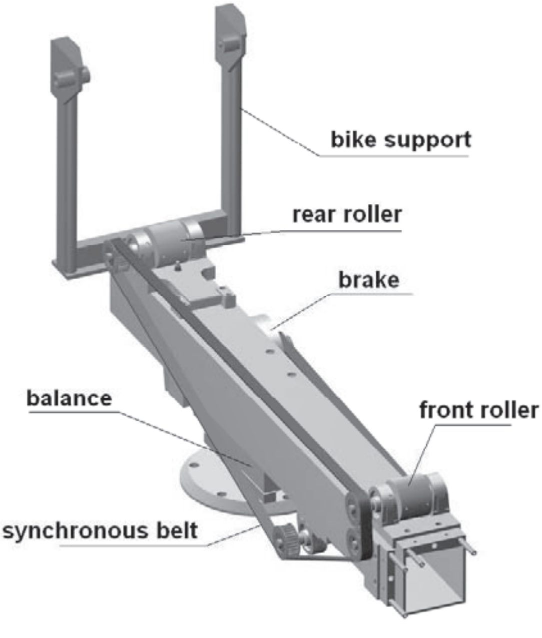
For this activities, a raised ground plane has been mounted in the test section slightly reducing its height from 3.84 m to 3.6 m. Nevertheless, as the biker and bike projected frontal area is about 0.3 m^2 the blokage is quite small (in the order of 2%).

The bicycle was fixed to a special strut with a six components balance below it. The strut is composed by a beam with a fork to fix the rear wheel axle and a couple of rollers (one under each wheel) connected by a belt in order to drive the front wheel too (Figure 3). The system provides an adjustable resistance torque to the rear roller producing a realistic rider effort and thus a realistic body attitude.

As the aim of the tests was the study of biker position a rather standard bike configuration has been used in both the two tests series: the frame was a rather traditional one (each athlete used it's own one) as well as the helmet. The clothes too were not extremely optimized (they were rather common ones) while a typical time trial wheels choose has been adopted (a lens disk



The bicycle fixed to the support



The support with the rollers and the balance

Figure 3. The system for cycling tests in GVPM wind tunnel

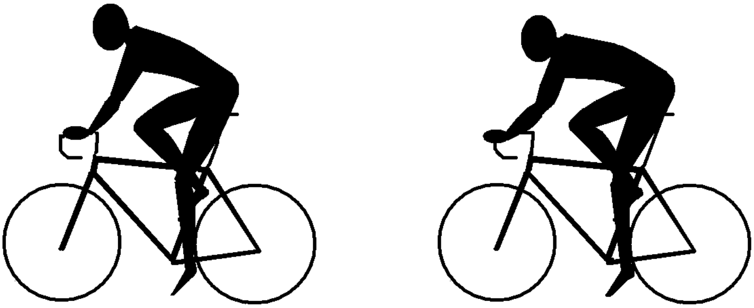
rear wheel and a 18 flat spokes aero-rim front wheel). The handlebars were traditional for the traditional positions while aero-bars have been used when time trial positions were tested.

Three typical traditional cycling positions have been tested (only two of them with biker A) while severall time trial positions (with different adjustement of handlebars) have been investigated with the biker A in order to identify the best position (i.e. the position with the smaller drag) and only a few slight variations around this optimal position have been tested with biker B. The three traditional positions were (following the nomenclature of Heil (2002)) the 'stem position' (upright torso position with the hands placed near the stem of the handlebars), the 'brake hoods position' (with the hands placed on the brake hoods as in the second sketch of Figure 4) and the 'drops position' (with the hands on the drops portion of the handlebar as in the third sketch of Figure 4). In Figure 5 the time trial position is sketched so that it can be compared with the other ones.

Figure 6, 7 and 8 shows the bikers inside the wind tunnel in the three traditional positions, while Figure 9 shows the optimal time trial position that produced a quite low drag area ($SC_x = 0.223\ m^2$ for biker A and $SC_x = 0.235\ m^2$ for biker B): the torso is horizontal to be aligned with the wind, the forearms are horizontal as well and the head is turned down (just maintaining a bit of forward visibility). In this attitude all the athlete body is pointed to reduce projected frontal area and to avoid to produce unnecessary lift. In Figure 10 the view from above shows the forearms kept attached each to the other.

A similar comparison between the fundamental biker positions has been presented by Grappe et al. (1997), based on measurements in field conditions. The athlete was 1.75m tall (as biker A) and the general bike configuration was the same as in the present GVPM tests (but they used less aerodynamic wheels). Of course there are a lot of details that can be different and the bikers antropometry was different (also for the 1.75m biker), but a comparison is nevertheless interesting (particolarly in terms of percent differences).

As can be seen in the Table 3 the values found for the drops position (that is assumed as reference position in the table) are quite similar and almost equal for the two less tall men (the larger drag of athlete B with respect to the other two ones is reasonably scaled with their dimensions). Considering all the tested positions they look in rather good agreement (in terms of percent difference respect to the reference drops position) with the exception of the time trial position for which the GVPM results show an higher drag reduction, in very good agreement between biker A and biker B. It has to be pointed out that the GVPM value is the result of a



The stem position. The brake hoods position.

The drops position.

Figure 4. The traditional positions.

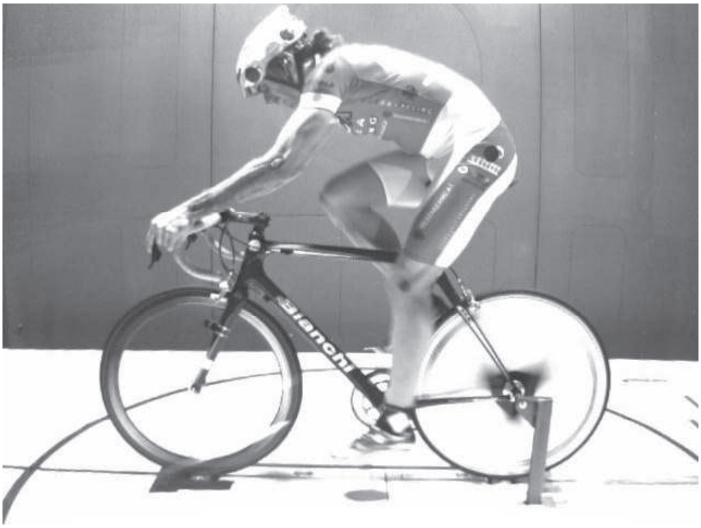
careful adjustment that may be was not carried out by Grappe et al., as they were more focalized on Obree's position. Therefore this comparison is very interesting as it suggests that results not so far from the ones that can be obtained with Obree's position can be achieved with regular time trial position.

It can be interesting to examine how muche these drag differences depends on the different projected area and how much they depends on the differences in the drag coefficients. In Table 4 the estimated frontal projected areas and the related drag coefficients C_x are presented and percent difference are reported again with comparison to the drops position.

The tabulated C_x values, so close to 1, demonstrated that biker is really a bluff body as espected. Nevertheless some non-negligible differences between the drag coefficient are present and it's rather interesting (and a bit surprising) that the smallest value is associated to the brake position (that,

Figure 5. The time trial position.

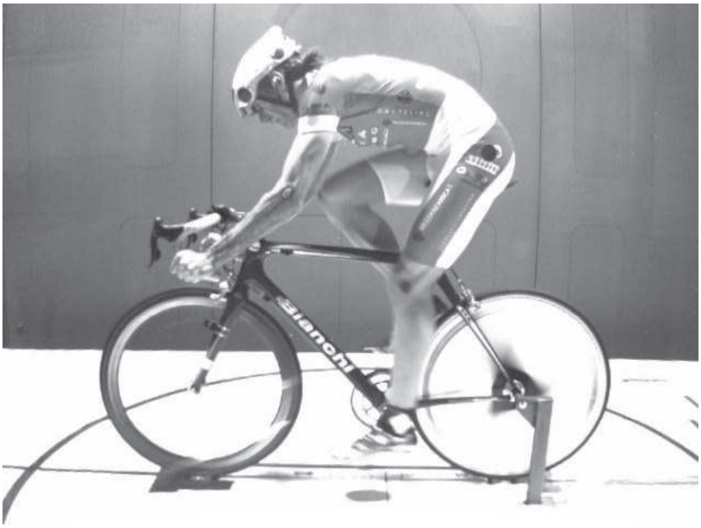
Figure 6. The stem positions in the wind tunnel tests (biker B).



Biker A

Biker B

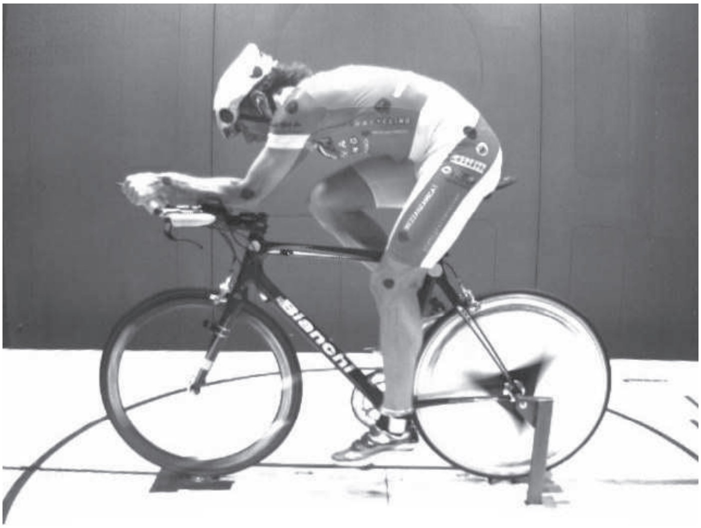
Figure 7. The brake hoods positions in the wind tunnel tests.



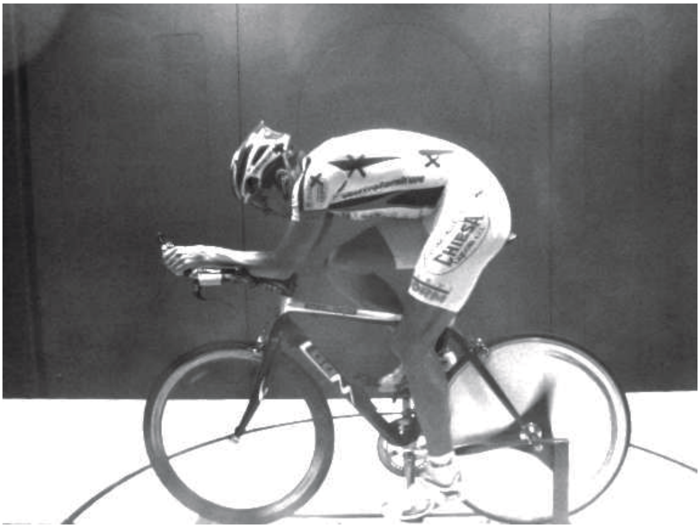
Biker A

Biker B

Figure 8. The drops positions in the wind tunnel tests.



Biker A



Biker B

Figure 9. The optimal time trial position.

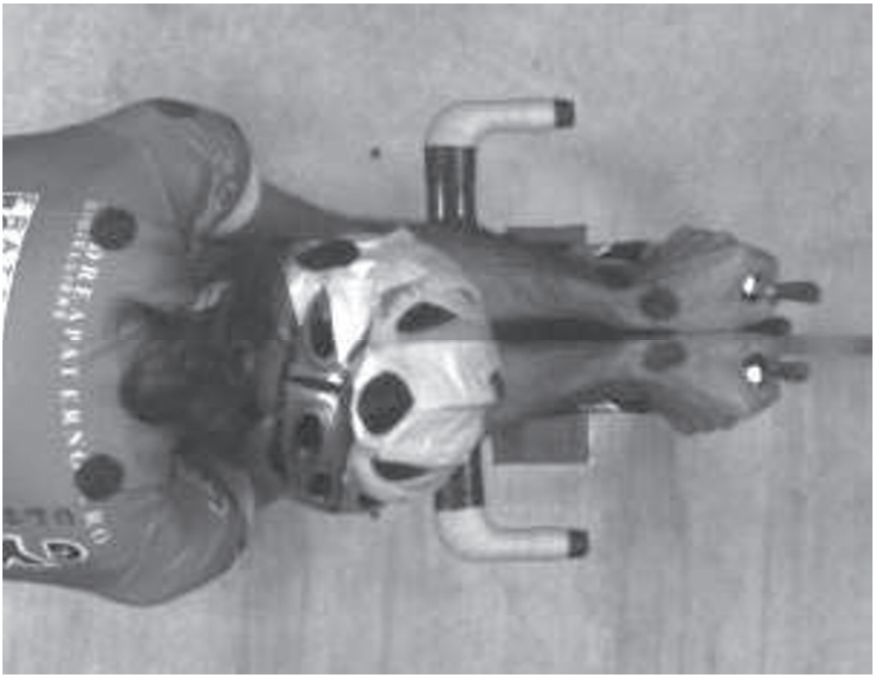


Figure 10. Time trial position seen from above: the detail of forearms

unfortunately, has the lergest area).

Of course, as already mentioned, these SC_x absolute values are specifically related to the specific athlete involved in the test: in the experience of the authors at GVPM, the best SC_x that can be obtained in time trial position varies from 0.20 m^2 to 0.29 m^2 depending on athlete size.

The head, the torso and, for a certain extent, the arms too, dont interact too much with the bicycle aerodynamics as they are rather above the bike structure but the same assertion is clearly not valid for the legs. Parker et al. (1996) have carried out a series of wind tunnel testing studying the interference between the legs and the bike frame. Two kind of frames has been used in the tests: a standard open frame and a particular (not UCI rules complying) closed aero-frame. They found that, for the standard frame, the best legs spacing is the standard spacing.

Table 3. Comparison between GVPM tests results and measurements in field conditions by Grappe et al. (1997).

Position	Grappe et al. (1997)		GVPM biker A		GVPM biker B	
	SC_x $[m^2]$	respect drops p.	SC_x $[m^2]$	respect drops p.	SC_x $[m^2]$	respect drops p.
Stem position	0.299	+8%			0.318	+10%
Brake hoods position			0.282	+3%	0.304	+5%
Drops position	0.276	0%	0.275	0%	0.289	0%
Time trial position	0.262	−5%	0.223	−19%	0.235	−19%
Obree's position	0.216	−22%				

Table 4. Projected frontal areas and drag coefficients for the different positions of biker B

Position	Projected frontal areas		Drag coefficient	
	S $[m^2]$	respect drops p.	C_x	respect drops p.
Stem position	0.386	+9%	0.824	+1%
Brake hoods position	0.400	+13%	0.760	−7%
Drops position	0.355	0%	0.814	0%
Time trial position	0.297	−16%	0.792	−3%

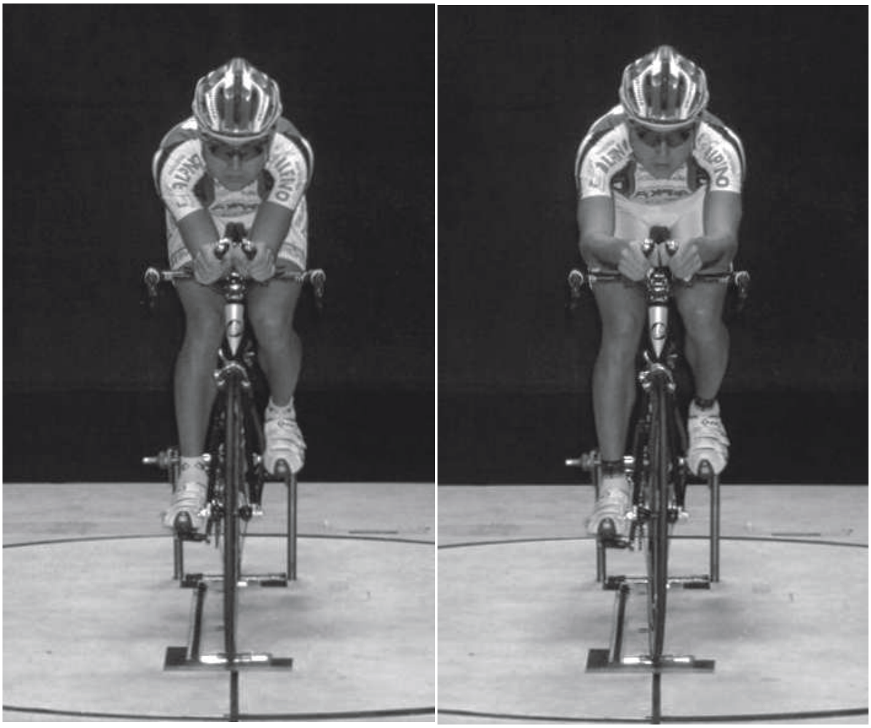
5.2 Ergonomics considerations

The present treatise doesn't undertake the complex problem of cycling ergonomics but some simple considerations can be made on the presented results. The proposed optimal time trial position is surely rather unconfortable and can jeopardize a good respiration so is reasonable to say that the remarcable advantage of this position would be really effective for short time-trial competition while a more confortable position should be considered in the case of a long race. As an example, a time-trial position essentially identical to the proposed optimal one but with the forearms slightly more separated can allow for a better respiration without to jeopardize too much the aerodynamic efficiency. In Figure 11 these two positions are showed from the front: the more "large" position produces an SC_x increase of 0.007 m^2 that corresponds to a 3%.

5.3 The head and the helmet

Beside the fact that the first aim of an helmet should be the head safety, it can be considered a sort of biker head fairing too. Actually, this was more true in the past (a streamlined helmet could reduce the SC_x, with respect to a traditional road helmet up to 0.02 m^2) but, nowadays, the more strict safety rules prescribes thicker helemets than, of course, have an higher SC_x (often not so different from the traditional ventilated helmet).

An interesting point is the head position. It's well known that some extreme aero-helmet that are designed for a specific head position work quite bad when the posture is not the required one, but this is not the only case where the head position is important. For example it can be interesting to observe the simple case of a biker wearing a traditional helmet: the two positions presented in Figure 12 have difference in the SC_x of about 0.002 m^2 (of course the less aerodynamic posture is the second one with the head turned up).



The “narrow” forearms posture. The “large” forearms posture.

Figure 11. The frontal view of two time-trial positions

6 The bicycle

6.1 The frame

The traditional frame is composed by round (or almost round) tube that are typically bluff bodies. Several attempts have been made to reduce the frame drag and actually from a traditional round tube frame to a very streamlined one (with airfoil shaped tube sections) the measured drag area (without anything but the frame itself) can decrease from a value around 0.05 m^2 to a value as small as 0.03 m^2. Unfortunately in the authors experience this rather valuable improvement is not replicated by the tests with the biker (that probably disturbs too much the flow around the frame, strongly reducing the effect of its sophisticated design).

Head down

Head up

Figure 12. Comparison between two head postures.

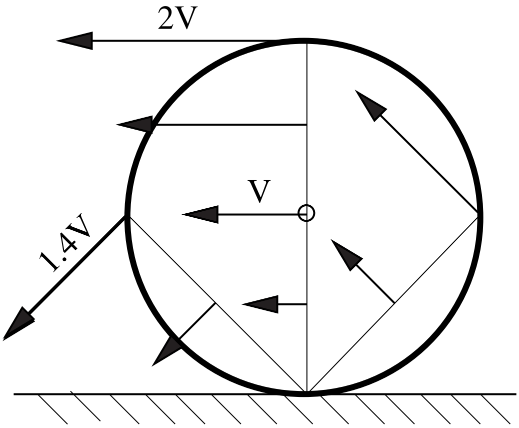


Figure 13. Rolling wheel velocities distribution

6.2 The wheels

The wheel aerodynamics has been widely study. As a matter of fact, although bicycle wheels have a very small frontal area, nevertheless they produce a non-negligible drag due to the fact that they have larger velocity above the axle (up to twice the bike velocity at wheel top as shown in Figure 13) and drag is proportional to the square of the speed (Sayers and Stanley, 1994).

Traditional wheels have a very poor aerodynamic as spokes, tire and rim section are all bluff bodies. Thus many solutions have been proposed in order to reduce the wake of tire and spokes. To reduce the wake of the tire, the rim is shaped in such a way the tire-rim section results to be more streamlined. On the other hand, to reduce the spoke energy dissipation their number is reduced and their section is aerodynamically shaped. The extreme results of this design philosophy are the three-spoke aero-wheels and the lens disk wheel. It's rather difficult to give definitive and general data about wheels drag as it can depends on small details of any commercial product. Generally speacking, tests carried out on isolated single spinning 700mm wheels (Kyle, 1990, 1991a) demostrades a drag area of about 0.024 m^2 for the traditional wheel (with 36 round spoke and standard rim) while much lower values have been found with the aerodynamic wheels, down to about 0.01 m^2 (with some lens-wheels or three-spoke wheels). In the cited tests, not only the air resistance force has been measured but also the aerodynamic resistant torque on the axle (this term too dissipates power, thus it has been reduced to an equivalent drag force and added to the real force in order to obtain a value that represents the total air resistance).

Actually a lot of model are proposed by manufacturers and is impossible to generalize and to say a priori which one is better. Furthermore the test of the wheel alone risks to be rather misleading as the important point is the whole bicycle behaviour. An important point is the effect of the wake produced by the biker legs and by the biker itself on the rear wheel (generally speacking, the wake is characterized buy a lot of turbulence and by a lower velocity).

A serious problem of disk wheels is their behaviour in cross-flow conditions (Tew and Sayers, 1999), particularly for the front wheel: the side aerodynamic force and the moment respect to the steering axis can produce severe driving difficulties (Suryanarayanan et al., 2002).

On the other hand, a problem with the three-spokes wheel is related to safety and up to now they are forbidden for massed start races (UCI, 2007).

In the experience of the authors, the lens disk is a very good choice for the rear wheel: due to its size with respect to the wake vortices size, the lens wheel has a stabilizing effect, while low solidity wheels (not disk) generally contribuites to turbulence increase and therefore produce a larger drag. On the contrary, the advantage of disk wheels is not so sensible in the front position when compared with other good aero-wheels (beside the fact that the front disk wheel is usually not used because it's very dangerouse in case of cross-wind).

Differently, comparing traditional rim wheels with low solidity aero-rim wheels, the larger difference is produced in the front position while the difference in the rear position is very lower. Two reasons can explain this fact: first of all, as already said, the velocity in the wake is lower and thus, in general, produces lower forces, then it has to be considered that the flow in the wake is quite irregular and probably the flow local velocities produce some separations also on the aero-rim.

Some tests were carried out at GVPM to measure the side-force at different crosswind velocities. In these tests only crossflow natural wind has been simulated as the longitudinal wind component was considered as due to the bike speed only and all the force cefficient were computed on the base of longitudinal dynamic pressure (i.e. computed on the base of the bike speed).

As an example, at 50 km/h with a 8.8 km/h crosswind (witch means a yaw angle of 10°) a side-force area SC_y from 0.31 m^2 to 0.45 m^2 was measured (depending on bike size and athlete size and position) when two lens wheels were used, while rather lower values (from 0.22 m^2 to 0.36 m^2) were

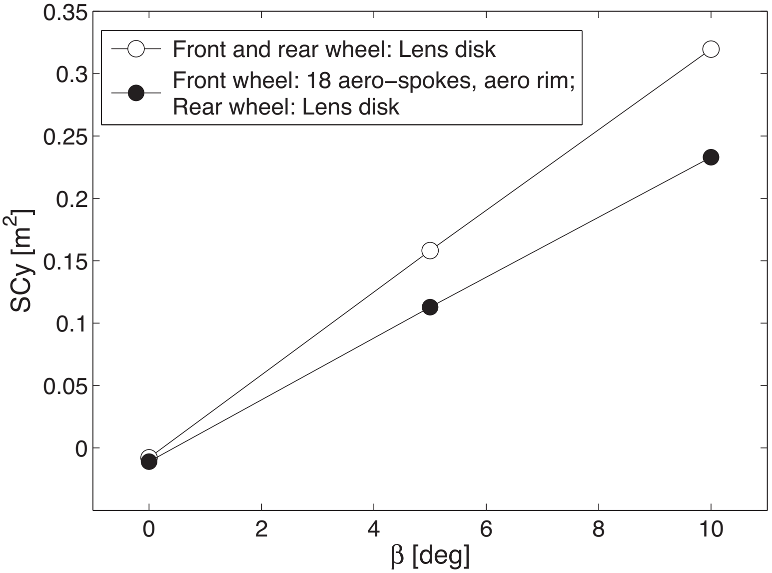
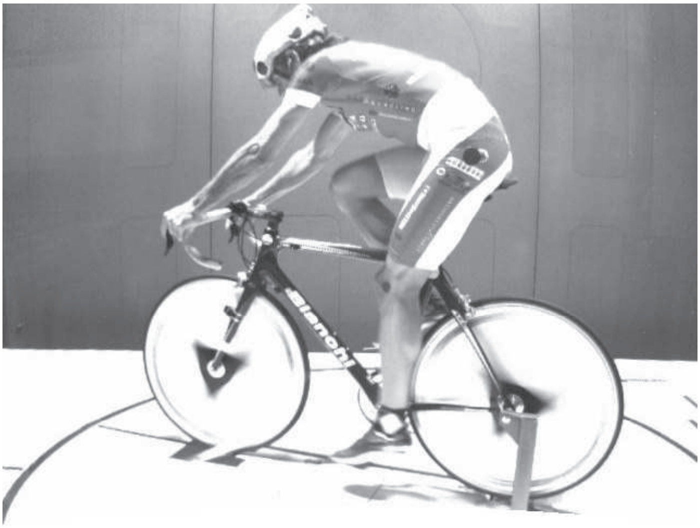


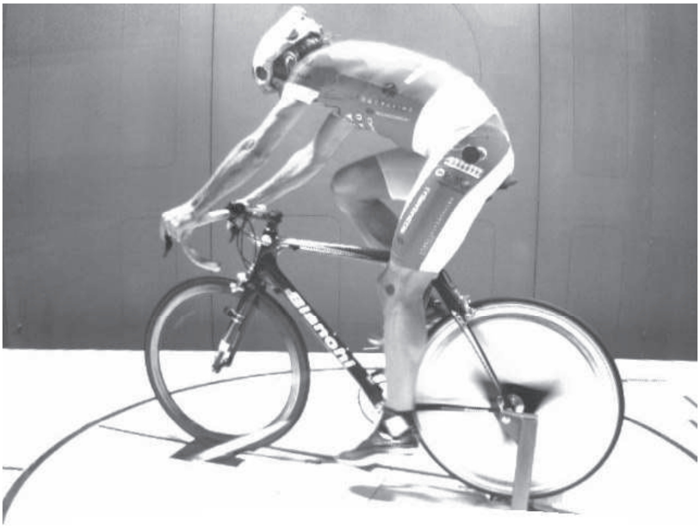
Figure 14. Measured SC_y for two different wheels combinations at different yaw angles.

obtained when the front lens wheel was substituted with a 18 flat spokes aero-rim wheel. Of course not all the side force is due to wheels but, in any case, the rather valuable difference between the two cited configurations (about 0.09 m^2) depends on the different front wheels.

A particular behaviour was measured by Tew and Sayers (1999) that registered a ‘jump’ in the lens disk wheel side force versus yaw angle: starting from zero yaw angle the side force grows linearly with the angle up to 5° then from 5° to 8° it decreases rapidly and then, starting from the 8° angle, it grows again with the initial slope. This rather surprising result was never repeated in GVPM measurements as can be seen, for example, in the graph of Figure 14 where a very regular and linear dependency of side force from yaw angle is clearly visible. These results refer to test carried out with the biker A in the traditional drops position (as can be seen in Figure 15). It’s also interesting to observe that, in presence of lateral wind the front lens wheel produces a rather relevant “sail effect” (it’s lift has a non-null component in the bike motion direction) that reduces the resistance. This is not, of course, the case of the spoked wheel (an holed sail is not a good



Test with lens disk front wheel.



Test with 18 spokes aero-rim wheel.

Figure 15. Crosswind tests at GVPM.

sail!). This effect was already observed by other authors (see, for example, Kyle (1991b))

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