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Drafting effect in cycling: investigation by wind tunnel tests

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Abstract

Cyclists travelling in groups experience a significant reduction in the wind resistance and those behind consume less energy due to the shielding effect of the front cyclist. We investigated drafting effects by wind tunnel tests realizing a test set-up with two cyclists pedalling at different longitudinal distance. Drag reduction effects on both the leading and the trailing cyclist are confirmed. The presence of lateral wind is also investigated showing a significant reduction of the drafting effect also for light winds.

Keywords: Cycling aerodynamics; drafting; lateral wind; wind tunnel tests

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1. Introduction

It is well established that wind resistance is responsible for most of the metabolic cost of cycling in level ground. Aerodynamic drag is about 80% of the total resistive force in road racing at 30 km/h and up to 94% in time trial competitions at 50 km/h, so that it becomes important to reduce it to improve cycling performance [1–4]. During races with multiple cyclists there is the opportunity to draft one another. Drafting is the practice by which individuals follow closely behind one or more other to limit the aerodynamic resistive force [5]. Drafting has also a significant application in team pursuit events [6]. Drafting effects have been less investigated with respect to the isolated rider aerodynamic optimization, although the magnitude of drafting can be impressive. Kyle[7] investigated the drag reduction in groups by coasting down tests and found a drag reduction in the trailing cyclist up to 44% while no effects have been measured on the leading cyclist. He observed, as expected, that the more closely one cyclist follows another the greater the drag reduction. Kyle investigated also the effect of alignment and showed a decrease of wind resistance from 0 to 30%, depending upon the amount of overlap and side spacing, compared to the 44% for the case of perfect alignment. Edwards and Byrnes[5] carried out field test with power meters installed on the bikes on individual and drafting cyclists with different leading and drafter athlete showing a pronounced variability of these data. In Edwards and Byrnes paper drafting effect ranges between 35 and 50%, depending on the leader characteristics and they measured also a minimal pushing effect on the leader that showed an average reduction of 1.63%. Blocken et al.[8] performed CFD simulations of the drafting effects as a function of the rider position and distance between bikes: Blocken et al.

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found a maximum reduction of 27.1% on the trailing cyclist and of 2.6% for the leading. 2-D numerical simulations performed by A Ìñiguez-de-la Torre[9] showed a possible benefit to the front cyclist of about 5%. In a recent paper Barry et al.[10] investigated the variation in aerodynamic drag for cyclists in both drafting and overtaking two rider formations. Different techniques are used nowadays to evaluate aerodynamic drag in cycling:on one side track testing allows a natural athlete's behaviour while, on the other side, wind tunnel testing is the most accurate and reliable technique [3,11]. In case of wind tunnel testing, particular attention should be given to the simulation of the pedalling with an adequate resistance, since significant differences are found between static and *in effort* tests [3]. In Broker et al.[12] the authors performed both wind tunnel and field tests on competitive team pursuiters finding out that the athlete in second position requires 70.8% of the power needed by the leader. Wind tunnel results showed a good agreement (67.7%), considering also that the rolling resistance was not included in this last value. In the present paper we investigate drafting effects by wind tunnel tests on two drafting cyclists, using a test set-up that allows the athlete to pedal with both wheels spinning. Particular attention is given to the effects of a small magnitude lateral wind.

Nomenclature

C_DA	drag area
D	drag force
d	distance between the bikes
U	wind speed
V	bike speed
V_r	wind speed relative to the bike
α	yaw angle
ρ	air density

2. Wind tunnel tests set-up

Tests have been performed in the Politecnico di Milano Wind Tunnel; the facility is a low speed and boundary layer wind tunnel located in the Politecnico di Milano technical university. To allow the positioning of two drafting cyclists the large test section of the facility has been used. The dimensions are 14 m wide and 4m hight; considering the typical frontal area of a cyclist of about $0.4\,m^2$ the blockage is very low ($< 1\%$). The maximum wind velocity is $16\,m/s - 57\,km/h$ and the turbulence intensity is equal to $I_u = 2\%$. The velocity profile is uniform except for the presence of boundary layers close to the walls and floor: in order to put the bikes outside the boundary layer a ground-board with height equal to $350\,mm$ was installed. Two racing bicycles with traditional wheels have been used as seen in Figure 1 where the layout of the test is also presented. Each bike is mounted on a supporting frame that has two vertical arms that fix the rear wheel axis. The wheels are placed over rollers so that the cyclist can pedal with an adjustable resistance. The two rollers are linked using a belt so when the athlete pedals the rear wheel moves and the belt transmits motion to the front wheel. In this way it is possible to test having both the wheels spinning at the same velocity. The main part of the support frame is located under the ground-board and it is connected to a 6-component force balance (RUAG strain-gauge balance model 192, X-f) and it is shielded to the wind. The two bikes are mounted on two different frames and the trailing bike one can be moved in order to adjust the distance between the bikes, having always the two bikes aligned with the hypothetical travelling direction. The distance, hereafter named d, is defined as the gap between the rear wheel of the leading bike and the front wheel of the trailing one as highlighted in Figure 1. Each bike is mounted on a force balance allowing us to have the simultaneous measurement of the drag on both bikes. The data were sampled at 500 Hz for 20 s: mean value is used in the analysis. During the tests videos are taken to identify and control the biker position.

The leading cyclist weights 77 kg and is 186 cm height while the trailing cyclist weights 70 kg and is 180 cm height. The biker position has obviously a significant influence on the drag value and it is often an important issue in the aerodynamic optimization: in this research we use the *brake hoods* position as reference and the athletes were asked to maintain the same position in all the tests. Tests were performed at $50\,km/h$ ($13.9\,m/s$) having a cadence of $100\,rpm$.

Figure 1. Cyclists layout in the wind tunnel. The distance *d* between the bikes is highlighted

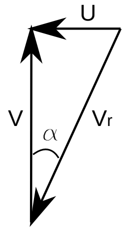


Figure 2. Velocity diagram in case of lateral wind

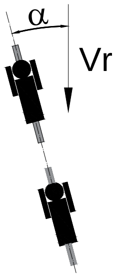
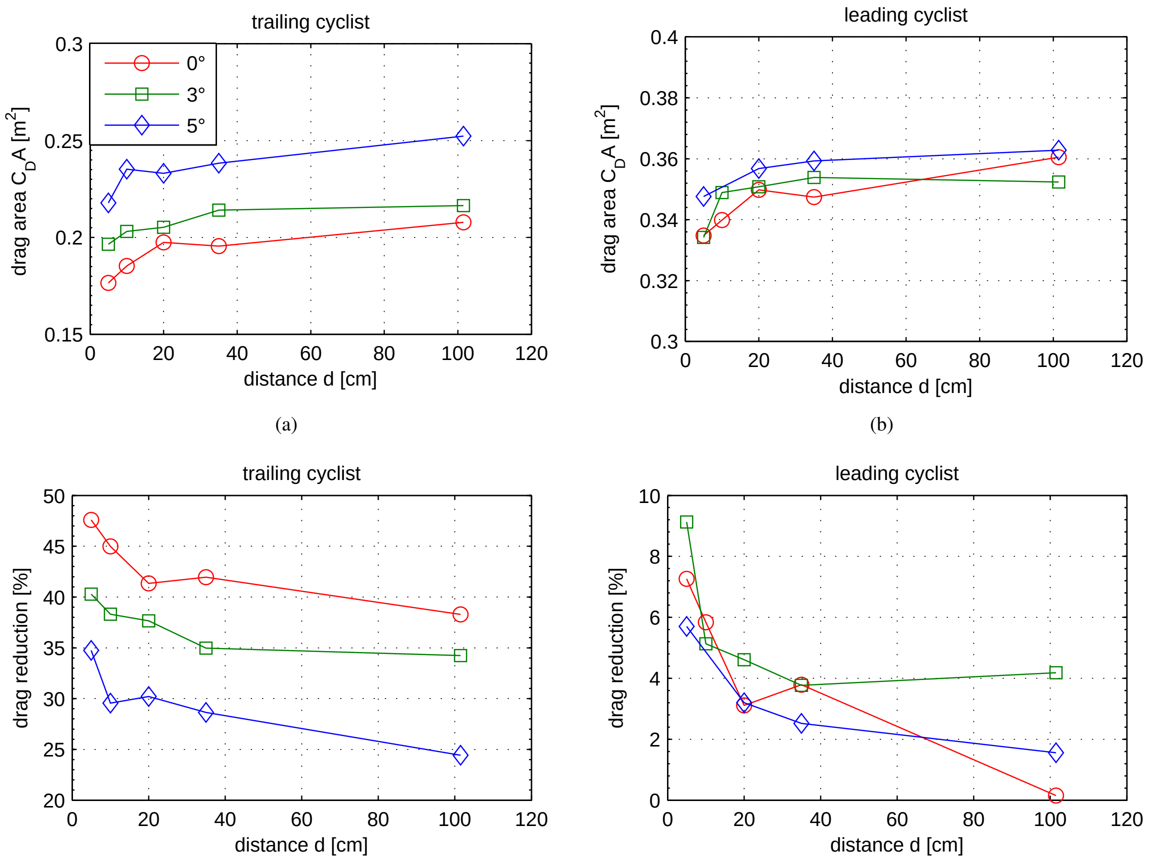


Figure 3. Bikes position in the wind tunnel for the lateral wind simulation

In case of a cyclist that is riding in still air the test wind speed corresponds to the actual bike velocity while this is not true in case of windy situations. In these cases the drag force depends on the relative wind velocity, as showed in Figure 2, that is not aligned with the travelling direction in case of lateral wind. In the graph a lateral wind of magnitude U is considered. To investigate this aspect we performed tests with the bikes slightly rotated with respect to the wind: this is possible by rotating the turntable of the test section of an angle α (Figure 3). Both bikes and force balances are fixed to the turntable and rotates integral with it. We considered angles of 3 and 5 degrees. In cycling aerodynamic drag is often expressed in the way of a drag area as

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

that is the ratio between the drag force D and the wind kinetic pressure $\rho V^2/2$. The drag area has the dimensions of an area $[m^2]$ and can be interpreted as the product of a drag coefficient and the frontal area of the cyclist. Of course the support frame will both affect the free air flow about the model and have some drag itself [13]. A *tare* has been measured by *wind on* tests on the support only and removed from the results. This procedure introduce a possible error since it is neglected the interference between the support and the model but it has been judged adequate for the purpose, in particular in the analysis of the differences between different test configurations. The balance was also zeroed before each test performing a *wind off* zero measure with the athlete in static position. In case of tests with lateral wind we decided to compute the drag area using the dynamic pressure calculated with respect to the theoretical bike speed V and the drag force is the wind force component aligned with the bike. Lateral wind force can also be important [2] but it is not presented in this paper. In wind tunnel testing on athletes particular attention should be given on the repeatability of the results. In fact, even if the instrumentation used has an high level of accuracy, the major source of uncertainty is the ability of the athlete to maintain the same position for all the duration of the test



(a) (b)

(c) (d)

Figure 4. Drag and drag reduction for trailing and leading cyclist as a function of the distance and for different wind directions

and (even more difficult) in all the different tests where he is assumed to repeat a reference position. In the author's experience the repeatability in consecutive tests leads to differences in C_DA up to 0.002 or 0.005 m^2, depending on the biker position (higher accuracy has been found in time trial position) while, during a long test programme, tests repeated at different times during the day have differences up to 0.008 m^2 that is in the order of 3%.

3. Experimental results

Drafting effects are evaluated studying changes in the aerodynamic drag in the different test layouts. Figure 4(a) and Figure 4(b) show the drag area of, respectively, the trailing and the leading cyclist. Results are showed as a function of the distance d between the leading and the trailing cyclist, d ranges from 5 to 100 cm. The three lines corresponds to a variation in the relative wind direction that is the presence of a lateral wind. 0° (red line) means no lateral wind while 3° (green line) and 5° (blue line) correspond to a lateral wind of, respectively, 2.6 and 4.4 km/h in case of a cyclist that is travelling at 50 km/h. With the aim of evaluating the advantage due to drafting a drag reduction coefficient has been evaluated as:

$$reduction_{trailing} = -\frac{C_DA_{trailing} - C_DA_{isolated}}{C_DA_{isolated}} \tag{2}$$

$$reduction_{leading} = -\frac{C_DA_{leading} - C_DA_{isolated}}{C_DA_{isolated}} \tag{3}$$

Table 1. Drag area for the isolated case ($C_DA_{isolated}$) for leading and trailing cyclist as a function of the relative wind direction

yaw (α)	trailing	leading
0°	0.337	0.361
3°	0.328	0.367
5°	0.331	0.366

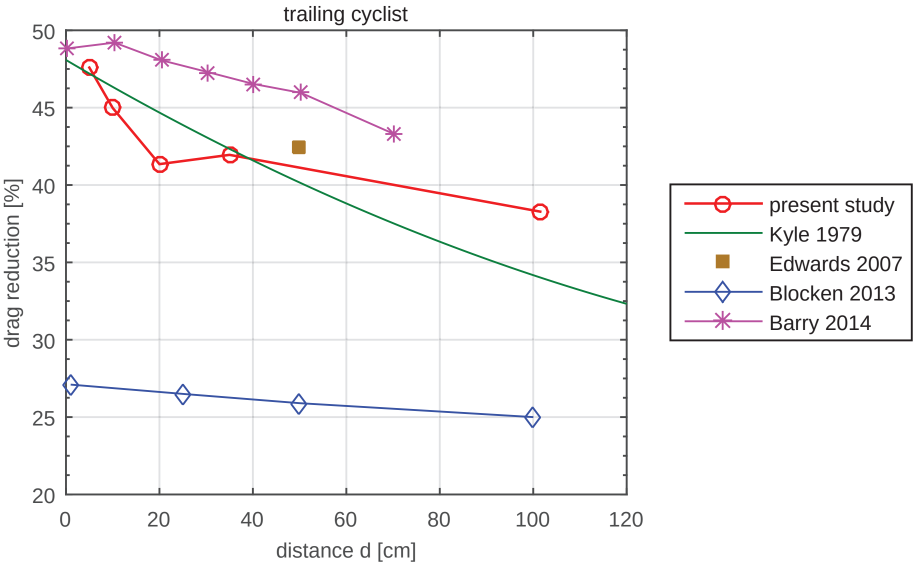


Figure 5. Drag reduction for trailing cyclist. Data from bibliography: Kyle[7] refers to field tests in *upright position*. Edwards and Byrnes[5] refers to field tests where subject maintain a racing position (hands gripping the dropped section of handlebars), average value. Blocken et al.[8] refers to body drag-only CFD simulations in *upright position*. Barry et al.[10] refers to wind tunnel tests on mannequins in *time trial position*.

where $C_DA_{trailing}$ is the drag area of the trailing cyclist in drafting position, while $C_DA_{isolated}$ is the reference value for the trailing cyclist stand-alone (the reduction for the leading cyclist is defined analogously). Since the *isolated* value depends, of course, on the biker body and position but also on the wind direction we evaluated this value in all the different cases investigated. The value has been measured having the trailing cyclist in his position on the ground-board and removing the leading bike and vice versa. For the trailing cyclist the absolute position on the ground-board was $d = 1\,m$ while for the leading the position is fixed. Table 1 reports the measured values. Drag reduction for trailing and leading cyclist is showed in Figure 4(c) and 4(d). In Figure 5 present results, for the case of perfect alignment (0°), are compared with selected bibliography results.

4. Discussion and Conclusions

Drafting is a well established method to reduce energy cost in cycling since the cyclists at the rear of a group experience less aerodynamic drag. This paper investigates the effect of drafting by wind tunnel tests that allow also the simulation of pedalling with effort. The present results match well Kyle's data measured in field tests confirming the decreasing trend of the drag reduction with the distance d. At the maximum distance investigated, about $1\,m$, a significant 38% of reduction is still present. Edwards and Byrnes[5] average value is also in good agreement with our data. Blocken et al.[8] found lower values with respect to ours and Kyle's data, but we have to consider that Blocken's results refers only to body drag and were obtained in static position. It seems also that in Blocken the decreasing rate of the force with the distance is lower. The magnitude of drag saving observed by Barry et al.[10] is comparable to the present work at close proximity d but is greater as the spacing increases. This may be due to a different biker position used by Barry (time trial position) and also by the different methodology based on static mannequins. To the authors' knowledge few informations are available for drafting effects in case of lateral wind. In group strategies riders arrange diagonally when lateral wind blows with the identical objective to save energy. This aspect is difficult to investigate accurately in track test since it is not possible to control wind magnitude and direction that can also vary randomly and fast. In wind tunnel testing it is easily possible to fix wind direction and make it possible to investigate lateral wind effects. Results in Figure 4(a) clearly show that the drag force experienced by the trailing cyclist increases as the wind angle increases. Since drag differences with wind angle in case of isolated cyclist are low (see Table 1) the large deviations in Figure 4(a) have to be imputed to the lateral wind. The drag reduction at $20\,cm$ drops from 41% at 0° to 30% at 5°. Experimental results shows also a non-zero effect on the leading cyclist drag. In fact, even if the drag reduction on the leading cyclist is small compared to the effects on the trailing one, a few percent of benefit is clearly visible: as for the trailing cyclist the reduction increases as the distance d decreases. Moreover we should note that also such a small difference can be important when we are dealing with few seconds time differences between athletes' performances. It is more difficult to identify the effects of the wind angle on the leading cyclist since differences are very small and comparable with the accuracy of the measurements. The main limitation of our study is that only longitudinal spacing has been investigated, having always the two bikes perfectly aligned with respect to the hypothetical running direction. On the contrary, in particular in lateral wind conditions, a side spacing should be also considered to identify optimal drafting position in windy days. An improvement of our wind tunnel set-up will make it possible in future tests.

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