Preliminary study on crosswind aerodynamics for a group of road race cyclists

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Abstract

Under crosswind conditions, road cyclists experience an extra drag force and a destabilising lateral force. In these conditions a group of cyclists manages to reorganise its spatial formation to minimise these forces forming an echelon, i.e. a diagonal single pace line of riders staggered across the road, a configuration which is markedly different from those adopted in wind-free conditions. To study the effect of the crosswind on drag and lateral forces on the riders we performed wind-tunnel experiments using a scale model cyclist and measuring the forces by means of a load cell. Several configurations with one, two, and four cyclists have been investigated varying yaw angles. Results show that, in a basic 4 rider configuration at a 50 ° yaw angle, a sheltered rider within the echelon experiences less than 30% of the drag of the guttered rider behind the echelon, struggling against the crosswind. Furthermore, we show that an echelon is worth being adopted under crosswind conditions only beyond a 30 ° yaw angle. At this critical 30 ° yaw angle the drag on the guttered rider doubles when the gap to the front group increases from 10 cm to 1 m (in real scale). These results can be of interest in defining road cycling race strategies and they allow some significant configurations to be identified and further investigated in more complex experiments.

Keywords Cycling aerodynamics · Echelon configuration · Load cell · Wind-tunnel experiments

1 Introduction

In cycling, the wind is a key factor as it generates extra drag forces (aerodynamic resistance) for the riders. On top of that, a strong enough crosswind can have a lateral destabilising effect and may even lead to a cyclist falling. Given that the drag (the force acting on the rider in the direction of travel) amounts to almost 90% of the total resistive forces for a cyclist at racing speeds [1, 2], it is interesting to know how much the drag and the lateral forces of one cyclist under windy conditions decrease through the shelter provided by a group of riders and which positions in the group are most beneficial in terms of force decreasing.

Slipstreaming effects and drag reduction in cycling groups and even larger pelotons with no wind are well known and have been highlighted by several previous wind-tunnel experiments [3, 4] and numerical simulations [5]. For instance, Blocken et al. [6] underlined that the drag of a rider in the mid rear of a peloton reduces to 5–10% of that of a solo rider and Blocken et al. [7] investigated the aerodynamic drag in cycling team time trials, in the absence of crosswinds, varying the number of riders and their wheel-to-wheel spacing. Barry et al. [8] studied the drag interactions of a four cyclist group by means of wind-tunnel experiments and they showed a significant reduction of the drag of about 50% for the sheltered riders with respect to an individual cyclist. Belloli et al. [9] investigated drafting effects by wind-tunnel tests for two cyclists

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pedalling at different longitudinal distance accounting also for slight lateral winds.

Under crosswind conditions, a group of riders adopts a different type of formation, such as echelon configurations (Fig. 1a). The riders are no longer in a paceline formation, riding one behind the other. They form a diagonal paceline in staggered positions across the road to counter crosswind effects. If the wind is coming from the right side of the road (e.g., see Fig. 1b), the leader of the group will ride on the right whereas the others will trail off to the left. Riders in the front “track” will move upward to the right, while riders in the back “track” will drift to the left, to keep the group riding as efficiently as possible. In professional cycling road races, it is well known that the guttered rider located just behind the echelon group struggles much more against the wind and is likely to get dropped from the pack (Fig. 1a). Some cycling team strategies consist in

forming such an echelon so that the opponents find themselves in this particular disadvantaging position [10, 11]. As a result the race often splits into several echelons that, from above, look like several diagonal lines chasing each other along the road (Fig. 1c). This phenomenon regularly occurs during the windy stages of long stage races (such as the Tour de France) and has a significant impact on the final general classifications. For instance, during the second flat stage of the 2015 Tour de France, from Utrecht to Zeeland (166 km), as a consequence of the formation of echelons caused by the crosswind, the peloton split into three groups. At the end of the stage Nairo Quintana arrived in the second group, losing 1'28" from Christopher Froome, who arrived in the first group [12]. The final yellow jersey of this edition of the Tour de France, i.e. the overall general classification winner, was C. Froome, whereas N. Quintana got the second place at 1'12"!

Fig. 1 Illustrations of echelon formations during a cycling race: **a** Schematic of an echelon formation; **b** Principle of an echelon formation during stage 2 of 2019 Paris-Nice race edition. The crosswind comes from the right [13]; **c** Helicopter view of several echelons during stage 2 of 2019 Paris-Nice race edition [13]

Several other examples—e.g. 2016 UCI road world championships in Qatar, the 2nd stage of 2019 Paris-Nice (Fig. 1b and c), and the 10th stage of the 2019 Tour de France—show that the flat stages characterised by crosswinds can be often more decisive than mountain or time trial stages and, therefore, the right management of the lateral winds can assume large importance in cycling strategies.

To date, most of the crosswind aerodynamics studies have focused on the impact of wheel geometries on the rider stability [14, 15] as well as on the drag reduction [16, 17] and they investigated the aerodynamics of a single road rider under crosswind conditions by performing wind-tunnel experiments and numerical simulations. It was highlighted that the drag coefficient for a solo rider reaches a maximum for a yaw angle around 15° . More recently, Mannion et al. [18] also performed CFD simulations and wind-tunnel tests to analyse crosswind aerodynamics of a solo hand-cyclist. Different positions of the rider and several wheel geometries were investigated for a range of yaw angles from 0 to 20° . A drag increment of 14% was measured between increasing yaw angles from 0 to 15° for a road race hand-cyclist.

Nevertheless, as far as we are aware, studies of aerodynamic drag and lateral forces in a group of road cyclists forming an echelon under crosswind conditions have not yet been performed. We have therefore addressed this issue by means of wind-tunnel experiments (Sect. 2). We present the results in Sect. 3. As a first step, we focus on the crosswind aerodynamics of a solo road rider (Sect. 3.1) and we compare our results with previous literature results. Subsequently, we analyse several configurations for a group of two cyclists and we present the drag and lateral force reduction experienced by the sheltered rider under crosswind conditions for different yaw angles (Sect. 3.2). Finally, a 4 rider echelon is studied to point out the differences in drag and lateral forces experienced by a sheltered rider in the echelon and a guttered rider struggling against the wind behind the group (Sect. 3.3). An extensive discussion about the main results is reported in Sect. 4.

2 Materials and methods

2.1 Experimental setup

This experimental study concerns wind-tunnel measurements carried out in the Laboratoire de Mécanique des Fluides et d'Acoustique at the Ecole Centrale de Lyon. This wind tunnel is 1.5 m long with a $40\text{ cm} \times 40\text{ cm}$ squared section. We used steel model cyclists at the scale $1/32$ of 5.5 cm high, 5.1 cm long, and 1.5 cm wide (Fig. 2a and b). The estimated frontal section of the model

is $S = 5.5 \times 10^{-4}\text{ m}^2$. This corresponds to a 1.80 m high cyclist adopting a road race position on a classical road race bicycle and it is consistent with the values found by other authors [3, 17].

A poly(methyl methacrylate) perforated grid was designed to fix each cyclist as required, in order to reproduce a given group formation (Fig. 2b and c). This grid is fixed on the lateral panel of the wind tunnel and can be rotated to introduce varying wind directions (corresponding to different yaw angle α_y). The cyclist placed in the middle of this grid is directly linked to an aerodynamic balance providing the force measurements (Sect. 2.2). During the measurements the grid holes that were not held by the models were suitably covered with duct tape in order to not influence the flow field.

During the experiments we imposed a free stream velocity equal to 25 m/s (close to the maximum possible speed of the facility) and we collected the values of pressure and temperature. The measurements were generally carried out at atmospheric pressure and 20°C , corresponding to an air density $\rho \approx 1.19\text{ kg/m}^3$. A Pitot tube provided value of the wind speed with an accuracy of $\pm 0.1\text{ m/s}$. We performed velocity measurements by means of a one-probe hot-wire anemometer. These showed that the boundary-layer height developing at ground level is less than 0.4 cm. This is below the feet and pedals of the model cyclist and should therefore not impact the accuracy of the forces measured by the load cell [6]. The measured value of the free-stream turbulent intensity is about 0.5%.

The Reynolds number of the flow is calculated as follows:

$$Re = \frac{Uc}{\nu}, \quad (1)$$

where c is the torso chord length [19], $\nu = 1.51 \times 10^{-5}\text{ m}^2/\text{s}$ the air kinematic viscosity at 20°C , and U is the flow speed. For a real scale cyclist riding at 40 km/h ($c = 0.7\text{ m}$, $U = 11\text{ m/s}$), we have $Re \approx 5 \times 10^5$. In our experiments, with a torso chord length $c = 2.7 \times 10^{-2}\text{ m}$ and a flow speed $U = 25\text{ m/s}$, we have instead $Re \approx 4.5 \times 10^4$, i.e. a value that is approximately 11 times smaller than that of a real scale cyclist riding at 40 km/h.

2.2 Force measurements

The drag and lift forces were measured by means of a load cell providing with an accuracy of $\pm 0.005\text{ N}$. The data were sampled at 10 Hz for 60 s, after a calibration process. An averaged value of the signal generated by the balance was then retained after a settling period of about 10 s in order to ensure the proper air speed in the wind tunnel. The force measurements were repeated

Fig. 2 Experimental setup: **(a)** Model cyclist at the scale 1/32; **(b)** Model cyclists in the wind tunnel; **(c)** Adjustable, perforated grid. The centre hole corresponds to the position of the rider directly linked to the load cell. The distances are expressed in mm

several times (about 5-10 times) and we estimated the experimental uncertainty as about $\pm 3\%$.

During the experiments the load cell provided a measure of the forces acting on the model rider in the direction of the flow (drag function of the balance, D) and in the direction orthogonal to the flow (lift function, L). Actually, the drag T_x experienced by the rider, i.e. the force in the direction of its move, and the lateral force T_y , i.e. the force in the direction orthogonal to the direction of the move are of interest (see Fig. 3). These target forces can be deduced by projection as follows:

$$T_x = D \cos \alpha_y - L \sin \alpha_y, \quad (2)$$

$$T_y = D \sin \alpha_y + L \cos \alpha_y. \quad (3)$$

From these we compute the non-dimensional coefficients C_x (drag coefficient) and C_y (lateral force coefficient), defined as:

Fig. 3 Measured forces in the wind tunnel (L , D) and target forces (T_x , T_y)

$$C_x = \frac{T_x}{\frac{1}{2} \rho S V_{wt}^2}, \quad (4)$$

$$C_y = \frac{T_y}{\frac{1}{2} \rho S V_{wt}^2}, \quad (5)$$

where V_{wt} is the velocity imposed in the wind tunnel experiments.

A clear distinction has to be made between the frame of reference of the real moving cyclist and that of the wind tunnel. The experimental values are presented in the frame of reference of the steady state cyclist for a given yaw angle. In reality, cyclists ride at speed U under a crosswind characterised by a velocity V_{cw} and a direction α_{cw} relative to the moving cyclist. This situation is equivalent to the case of a steady model cyclist placed in the wind tunnel and subjected to an air flow with a velocity V_{wt} and a yaw angle α_y , as shown in Fig. 4.

With some algebra, the wind-tunnel parameters (V_{wt} , α_y) can be expressed as a function of the crosswind parameters (V_{cw} , α_{cw}), as follows:

$$V_{wt} = \sqrt{(U + V_{cw} \cos \alpha_{cw})^2 + (V_{cw} \sin \alpha_{cw})^2}, \quad (6)$$

$$\alpha_y = \arctan \frac{V_{cw} \sin \alpha_{cw}}{U + V_{cw} \cos \alpha_{cw}}. \quad (7)$$

For sake of completeness we report also the relation between the yaw and real angle:

$$\alpha_{cw} = 2 \arctan \frac{1 - \sqrt{1 - (\tan \alpha_y)^2 (U/V_{cw})^2 + (\tan \alpha_y)^2}}{(U/V_{cw} - 1) \tan \alpha_y}, \quad \text{if } U \neq V_{cw}, \quad (8)$$

$$\alpha_{cw} = 2\alpha_y, \quad \text{if } U = V_{cw}.$$

Fig. 4 Crosswind parameters in reality and in the wind tunnel: **(a)** Real crosswind parameters (B. Hinault during the stormy and snowy 66th running of Liège-Bastogne-Liège, 1980); **(b)** Steady rider and equivalent parameters in the frame of the wind tunnel. The velocities V_{cw} , U , and V_{wt} in the figure have to be seen as three vectors

In order to make the analysis more intuitive we also provided the results in the real frame of reference, where α_{cw} is computed for a crosswind velocity $V_{cw} = 40$ km/h and a cyclist velocity $U = 40$ km/h that is typically close to the average speed of a professional road cycling race, such as a flat stage of the Tour de France.

2.3 Shortcomings of the study

This study is affected by some simplifications and approximations and, therefore, the results have to be considered as preliminary. Nevertheless, we believe that some particularly interesting configurations can be identified and they shall be further investigated in more complex experiments. The main shortcomings of our study are the following:

1. The experiments were carried out at $Re = 4.5 \times 10^4$ and, therefore, the flow conditions cannot be considered as similar to those of a full-scale rider. Note that quantifying the effect of these variations in Re is not straightforward based on literature data since, as far as we are aware, an exhaustive study on influence of the Reynolds number on the cyclist aerodynamics is still lacking. Further discussion on this feature is provided in Sect. 4.1.
2. The cyclist models are static, although the riders aerodynamic drag varies during pedalling [4].
3. The positions of the riders on the grid (Fig. 2c) vary in a discrete way since the minimal distance between two

holes is equal to 1 cm.

4. The geometry of our cyclist model was rather coarse and it presents several approximations with respect a real rider. It was not designed from a real professional cyclist (with a 3D scanner for instance) and its design neglects smaller scale details (e.g., absence of the wheel spokes, simplified mechanical elements of the bicycle as chainset, brakes, derailleurs, flat arms on the inner side, etc.). Furthermore, the position of the rider was not optimised: professional cyclists in crosswind conditions often keep their hands on the bottom of the handlebars, they adopt a head-down position for both aerodynamic and stability purposes, and, in order to compensate the torque due to the lateral force, they

assume a tilted position with respect to the road and steer into the wind [20].

3 Results

The experiments were performed on three main configurations varying the wind direction. Firstly, we considered the aerodynamics of a single rider in order to compare and validate our measurements against the data available in literature. Then, we studied two riders aerodynamics and we performed force measurements on the sheltered rider varying the position of the front cyclist. That allowed us to identify the most profitable configurations for the rider in the wake and to estimate the reduction of C_x and C_y with respect to a solo cyclist. Finally, we interested in a four-rider echelon and we analysed the differences of the drag and lateral forces experienced by the third (sheltered) and the forth (guttered) cyclist in plausible race situations.

3.1 Single rider aerodynamics

A single model rider was placed in the wind tunnel in order to analyse the C_x and C_y coefficients as a function of the wind direction α_y . We compared our experimental values with the experimental results and the RANS (Reynolds Averaged Navier-Stokes) simulations (with turbulence models $k-\varepsilon$ and $k-\omega$) performed by Fintelman et al. [17] for the same type of study (Fig. 5).

These results confirm the existence of a critical yaw angle around 15° (corresponding to $\alpha_{cw} = 30^\circ$ for plausible race conditions $U = 40$ km/h and $V_{cw} = 40$ km/h) for which the drag coefficient reaches a maximum, as shown in previous studies [16, 17]. A drag increase of 11% is measured between 0 and 15° , which is in agreement with the

similar 14% drag increase value for a solo road hand cyclist observed by Mannion et al. [18]. Consequently, a solo road cyclist has to produce more power at a 15° yaw crosswind than a cyclist riding as fast and facing a pure headwind with a similar velocity. A quasi linear decrease of the drag coefficient then occurs between 20 and 90° yaw angle. At a 90° yaw angle the drag coefficient only amounts to 14% of its maximal value. The overall increase of the side force coefficient with the yaw is also confirmed. At a 90° yaw the side forces are twice higher than at a 45° yaw. Beyond 45° the side forces become higher than the drag forces which show how much a strong crosswind can laterally destabilise a solo rider.

For both coefficients a good agreement is found between our experimental data and the $k-\varepsilon$ RANS simulations performed by Fintelman et al. [17], with a maximal difference of 14% for the drag coefficient and 12% for the side force coefficient at 60° . For all other yaw angles tested, the difference is less than 5%. Larger differences up to 15% for yaw angles between 0 and 30° are observed with the $k-\omega$ turbulence model. As pointed out by Fintelman et al. [17], this is due to the inability of this turbulence model to correctly reproduce the flow separation and attachments. Likewise differences up to 18% are noticed for the side force measurements by Fintelman et al. [17], whereas the differences between the drag coefficients remain lower than 5% (for each yaw angle except 60° where a 10% difference is noticed).

The discrepancies between the different sets of data may arise from the uncertainty in estimating the frontal area S of the cyclist model and from its simplified geometry (see Sect. 2.3). Notably, in crosswind conditions the wheel geometry substantially impacts the stability of the rider [14, 15] and, therefore, the lateral-force measurements may have been significantly different with larger or

Fig. 5 C_x (a) and C_y (b) coefficients as a function of the yaw angle α_y . Comparison between our experimental data and numerical and experimental results by Fintelman et al. [17]. The vertical bars in the

experimental values of the current study represent an uncertainty of about $\pm 3\%$ in the force measurements (see Sect. 2.2)

smaller wheel rims. Other differences between our data set (with $Re \approx 4.5 \times 10^4$), the experiments by Fintelman et al. [17] ($Re \approx 5.0 \times 10^5$) and their RANS results can be in principle due to the effect of a varying Reynolds number. This aspect will be extensively discussed in Sect. 4.1.

3.2 Two riders aerodynamics

Nine different configurations with two riders were studied to determine which one is the most beneficial for the sheltered rider (referred to as rider 2) in terms of drag and side force reduction for different crosswind directions. Drag and lateral forces are measured for the rider 2 placed on the load cell in the centre of the grid and a comparison is made with the values corresponding to an isolated rider.

The grid is oriented to simulate a crosswind coming from the right relative to the direction of the cyclists. In these configurations, the rider 2 benefits from the wake of the front rider providing a shelter from the crosswind. For each configuration, four crosswind directions α_y were investigated: 5° , 15° , 25° , and 45° . The constant flow velocity imposed in the wind tunnel was $V_{wt} = 25.0$ m/s. The results are also expressed in the real frame of the moving cyclist group (riding at the speed $U = 40$ km/h) under a $V_{cw} = 40$ km/h (11.1 m/s) crosswind and in these hypothetical race conditions $\alpha_{cw} = 10^\circ$, 30° , 50° , and 90° (see Fig. 4 and Eq. 8).

Since the step between two holes of the perforated grid in which the models are fixed is equal to 10 mm (see Fig. 2c), a real lateral distance between the two riders of 32

Fig. 6 Description of the 9 different configurations tested

cm (Conf. 2), 64 cm (Conf. 3), and 96 cm (Conf. 4 to 9) can be simulated, as shown in Fig. 6. These are realistic values in a cycling peloton where the riders use to ride very close to one another (Fig. 1b). In each case, the drag (or lateral force) of the sheltered rider 2 is expressed as a percentage of the drag (or lateral force) of an isolated cyclist riding at the same speed under the same yaw angle crosswind.

For a relatively small yaw angle of 5° , the best configurations in terms of drag reduction are Conf. 1 and Conf. 2 (Fig. 6), where the sheltered rider's bicycle is fully behind the leading cyclist. Other configurations do not provide a relevant drag reduction as the sheltered rider is not sufficiently protected by the leading one to fully benefit of the wake for this particular values of α_y (Fig. 7a). The best configurations, in terms of lateral forces reduction, are Confs. 2 and 3 with a reduction down to 40% that of a single rider in the same conditions.

It is interesting to notice that no significant difference is observed between the 15° yaw angle and the 25° yaw angle configurations (Fig. 7b and c). In these two cases, the best configurations with respect to both drag and lateral force reduction are Confs. 2 and 3, where the

sheltered rider remains behind the leading one with a lateral gap between them. These configurations are far more efficient than the classical paceline configuration (Conf. 1) adopted in wind-free conditions. Furthermore, configurations 4 to 9 still do not enable rider 2 to fully benefit from the wake of the leading cyclist. The closer rider 2 gets to the front rider longitudinally, the less rider 2 is placed in the wake.

As the yaw angle increases from 25 to 45° ($\alpha_{cw} = 50^\circ$ and 90° in race conditions $U = V_{cw} = 40$ km/h), the results become drastically different. The best configurations in terms of both drag and lateral forces reduction become Confs. 4, 5, and 6, whereas Confs. 1, 2, and 3 barely provide any drag and lateral force reduction. In other words, for this type of large yaw angle crosswind, a rider has to get closer longitudinally to the front rider to be in the wake as much as possible. Such a brutal change of optimal configurations between 25 and 45° yaw angles might arise from a separation of the air flow around the front rider changing the shape of the wake. Configurations 8 and 9, where the two riders are almost side by side, are not relevant as rider 2 gets out of the wake.

Fig. 7 Drag and lateral force reduction provided to the sheltered rider for 4 different yaw angles: a) $\alpha_y = 5^\circ$ ($\alpha_{cw} = 10^\circ$); b) $\alpha_y = 15^\circ$ ($\alpha_{cw} = 30^\circ$); c) $\alpha_y = 25^\circ$ ($\alpha_{cw} = 50^\circ$); d) $\alpha_y = 45^\circ$ ($\alpha_{cw} = 90^\circ$)

For the Confs. 7, 8, and 9 at 25 ° yaw and the Confs. 1 and 2 at 45 ° yaw, the lateral force reaches a percentage between 103% and 108% of that of an isolated rider. Such a difference with the lateral force of a solo rider may not be attributed to a measurement error as the accuracy provided by the balance is $\pm 3\%$. As a result, it seems that rider 2 in these positions experiences an even larger lateral force than if he is alone.

3.3 Echelon configurations with 4 riders

A typical echelon formation is now investigated. Three riders are used to create an echelon across the road width while the fourth one is placed in the position of the guttered rider (Figs. 1a and 8).

Fig. 8 Echelon configuration tested

The grid is oriented to simulate a crosswind coming from the right relative to the direction of the cyclists. For each configuration, 10 yaw angle α_y were investigated: 5 °, 10 °, 15 °, 20 °, 25 °, 30 °, 35 °, 40 °, 45 °, and 50 ° (corresponding, respectively, to the real crosswind directions $\alpha_{cw} = 10^\circ, 20^\circ, 30^\circ, 40^\circ, 50^\circ, 60^\circ, 70^\circ, 80^\circ, 90^\circ$, and 100° for riding at the speed $U = 40$ km/h under a $V_{cw} = 40$ km/h crosswind). The position of the 4 cyclists on the grid is based on the results provided by the 2 rider analysis. The drag and the lateral force of riders 3 and 4 are measured and compared to the same values for an isolated rider in the same crosswind conditions and riding at the same speed. As previously, the fixed flow velocity imposed in the wind tunnel is $V_{wt} = 25.0$ m/s.

For yaw angles lower than 30 ° ($\alpha_{cw} < 60^\circ$) we notice that rider 4 experiences a drag 25% lower than that of rider 3 in a sheltered position (Fig. 9a). In other words, for these relatively small yaw angles it is more beneficial to be behind the echelon than riding within it. With regard to the lateral forces, the values for rider 3 are barely lower than for rider 4; no significant disadvantage is identified for rider 4 (Fig. 9b).

Yet for $\alpha_y > 30^\circ$ ($\alpha_{cw} > 60^\circ$) a sharp increase in the drag of rider 4 is observed whereas the drag of rider 3 continues to decrease. The same phenomenon is pointed out for the lateral forces. At 50 ° yaw, the guttered rider experiences the same forces globally as an isolated rider, whereas rider 3 is very well sheltered in the echelon, with drag and lateral forces of 29.6% and 20.6% of an isolated rider, respectively. The drag and lateral forces are therefore 3.4 and 4.9 times smaller than the those of the guttered rider, respectively.

Finally, we focus on what happens at the critical yaw angle of 30 ° (before the sharp increase of drag is observed) if rider 4 is slightly dropped from the echelon group. Table 1 shows the impact of the gap between the front wheel of rider 4

Fig. 9 Comparison of the drag (a) and lateral forces (b) of riders 3 and 4 in the echelon with respect to the values experienced by an isolated rider. The vertical bars represent an uncertainty of about $\pm 3\%$ in the force measurements (see Sect. 2.2)

Fig. 10 Gap d between rider 4 and rider 3

Table 1 Drag and lateral forces at 30° yaw of rider 4 as a function of the gap d between riders 3 and 4 (expressed as a percentage of the values for an isolated rider in the same conditions)

Gap d (mm)	3	13	23	33
Real scale gap (m)	0.1	0.42	0.74	1.06
Drag	40.4%	52.1%	70.3%	89.5%
Lateral force	45.2%	55.7%	83.2%	94.8%

and the rear wheel of rider 3 (as illustrated in Fig. 10) at a 30° yaw. Professional cyclists ride relatively close to one another in a peloton (Fig. 1b), with a gap between 5 cm and 30 cm [21]. For these values and at this particular yaw angle, rider 4 remains well sheltered by the front group. Nevertheless, we observe that rider 4 experiences significantly increasing forces as the gap rises. For a real scale gap of 1.06 m (corresponding to 3.3 mm in the model), rider 4 really starts to struggle against the crosswind and large difference of forces is noticed compared to rider 3 whose drag and lateral forces are 3 and 4.8 times lower, respectively. For this critical yaw angle of 30° , a cyclist finding themselves in the disadvantaging position of rider 4 is very likely to get dropped if a gap occurs between him and the front group. This phenomenon is less substantial for yaw angles larger than 30° for which rider 4 experiences high forces regardless of the gap with rider 3.

4 Discussion

4.1 Single rider aerodynamics

The comparison between our wind-tunnel measurements on a single rider and other data sets [17] presented an

overall good agreement (Fig. 5). The results of different studies reproduce clearly a same trend of variations of C_x and C_y depending on α_y . Looking closely to the reported values we can however identify discrepancies between the different data sets. Beside eventual variations induced by simplified estimates of the frontal area and on several simplifications in the model geometry, these discrepancies arise the main question about the role of a varying Re on the drag coefficient.

In literature the dependence of the coefficients C_x and C_y on Re for a cyclist has been tackled in relatively few studies. Defraye et al. [22] investigated the drag area varying the position of the cyclist by means of wind-tunnel experiments. They performed measurements of the drag force of a full-scale cyclist for different values of the Reynolds number ($Re_1 \approx 4.6 \times 10^5$, $Re_2 \approx 7.0 \times 10^5$, $Re_3 \approx 9.3 \times 10^5$) and they did not observe any differences. Crouch et al. [4] studied the three-dimensional flow topology around a full scale cyclist by means of wind-tunnel experiments. They performed measurements of aerodynamic drag forces, time-averaged wake surveys, skin friction flow visualisation, and time-averaged surface pressure measurements. They varied the Reynolds number in the range $Re = 6.9 \times 10^5$ and $Re = 10.8 \times 10^5$, and they did not find any observable effect on the pressure distribution and flow separation/reattachment. Barry et al. [23] performed PIV measurements in a water channel using a 1:7 scale model cyclist at $Re = 3.3 \times 10^4$. They compared the vorticity fields with those presented by Crouch et al. [4]. The comparison showed that the results of the scale model are very similar to those of full scale and the two configurations exhibited the same primary wake structures. They concluded that the influence of the Reynolds number is negligible except for an increased rate of dissipation in the vorticity. Crouch et al. [19] performed PIV measurements in a water channel using a 1:4.5 scale-model cyclist at $Re = 5.7 \times 10^4$. They compared the vorticity fields computed from PIV data with those obtained in wind-tunnel experiments using a full-scale mannequin at $Re = 6.9 \times 10^5$. Despite the large difference in Reynolds number, they observed a good agreement between the flow fields of both configurations. Among the studies highlighting the effects of the Reynolds number on the cyclist aerodynamics we mention Terra et al. [24] that experimentally investigated the Reynolds number influence on the wakes of the arms and legs of a model cyclist varying the velocity in the range 5–25 m/s ($Re = 2.3 \times 10^5$ – 1.2×10^6) by means of PIV measurements in wind tunnel. They estimated the drag coefficient in terms of the change in wake width and they observed a reduction of C_x induced by the body limbs increasing Re , namely in the mid arm region and in the lower leg region. D'Auteuil et al. [25] studied the behaviour of the drag coefficient as a function of the Reynolds number for

a speed skater and they found that some positions of the skater (characterised by different drag areas) presented large variations of C_x with respect to an increase of the Reynolds number.

This overview on literature results enlightens that a full characterisation of the dependence of the coefficient C_x and C_y on Re is still lacking. Unfortunately, our experimental setup does not allow us to fill this gap (Sect. 2.3). However, the good overall agreement between our data (collected at $Re \approx 4.5 \times 10^4$) and the measurements performed by Fintelman et al. [17] at $Re \approx 5.0 \times 10^5$ (Fig. 5a and b) suggests that, despite we can not consider in principle our setup as representative of a full scale cyclist in real race conditions, the variations of the Reynolds number in the range $4.5 \times 10^4 \leq Re \leq 5.0 \times 10^5$ have a moderate impact on the coefficients C_x and C_y . More precisely, we can assert that the results in Fig. 5 show that the eventual influence of a varying Re is significantly lower than that of the wind incident angle α_y , i.e. the dependence on which we aim to focus in this study.

4.2 Two riders aerodynamics

The results presented in Sect. 3.2 allow us to identify the optimal configuration for the tested yaw angle and to quantify the corresponding decrease of drag and lateral forces (Table 2).

The drag reduces as the yaw angle increases and, expressed as a percentage of the drag for an isolated rider, it decreases from 50.3% to 31.2%. For a group riding at a speed of $U = 40$ km/h, this corresponds to equivalent cycling speeds of the sheltered rider of 28.4 km/h and 22.3 km/h, respectively (we define the equivalent cycling speed as the speed of an isolated rider that would yield the same reduced drag as that of the sheltered rider). Note that these are very easy speeds to maintain for professional riders. An isolated cyclist riding on a flat road at 40 km/h under a crosswind of 40 km/h and $\alpha_{cw} = 90^\circ$ ($\alpha_y = 45^\circ$) requires a power of about 560 W (this is only an approximation based on the drag value, many other factors have to be taken into account for a more accurate estimate, see, e.g., [26]). Such a power can be maintained for 5 to 30 minutes for a professional rider. With respect to the previous

results, a shelter rider in Conf. 6 would produce only 174 W (that is 3.2 times lower), a power that can be easily supplied for several hours [27].

The lateral force reduces to 25.9% (and 39.5%) that of an isolated rider at a 25° (and 45°) yaw angle, which means that the sheltered rider experiences about 4 times (and 2.5 times) less destabilising effects than the front rider. Consequently they will use far less energy to stay stable on the road.

4.3 Echelon configurations with 4 riders

The experiments on the echelon formation (Sect. 3.3) highlighted that, for yaw angles larger than 30° , the rider 3 (sheltered) benefits of a significant decrease of drag and lateral forces with respect to the cyclist 4 (guttered) riding behind the echelon. In the specific case of $\alpha_y = 50^\circ$ the rider 4 experiences drag and lateral forces close to those of an isolated cyclist, whereas for rider 3 C_x and C_y are approximately 3.5 and 5 times lower (Fig. 11). In the same way, as we have previously illustrated in the two-rider experiments (see Sect. 3.2), for an echelon riding at 40 km/h, under crosswinds of 40 km/h and $\alpha_y = 50^\circ$ (and $\alpha_{cw} = 100^\circ$), the power provided by rider 3 is 170 W approximately. Compared to 560 W for rider 4, this means a saving of 390 W. Hence, the echelon configuration would be worth being adopted during a race by a cycling team for yaw angles higher than 30° ($\alpha_{cw} > 60^\circ$). In practice, this result corresponds to the descriptions found in cycling newspaper articles stating that an echelon often occurs under “a 3/4 head wind”, i.e. a real angle α_{cw} around 60 – 75° .

Fig. 11 Drag and lateral forces in the echelon for a 50° yaw angle (expressed as a percentage of the values for an isolated rider in the same conditions). Note that for this configuration we collected also the forces experienced by rider 2

Table 2 Optimal configurations for the sheltered rider in terms of drag and lateral force reduction (expressed as a percentage of the drag/lateral force of an isolated cyclist riding at the same speed under the same crosswind)

Yaw angle	5°	15°	25°	45°
Optimal configuration	2	2	3	6
Drag	50.3%	44.4%	43.2%	31.2%
Lateral force	40.7%	48.5%	25.9%	39.5%

[10, 28]. The significant difference of power between the sheltered (≈ 170 W) and the guttered (≈ 560 W) rider could explain why so many splits are observed during a race under strong crosswind conditions. Conversely, under 30° yaw, no particular benefit would be drawn from an echelon as rider 4 in the supposed critical position would be even better sheltered than a rider which is placed within the echelon.

It should be stressed that, in the echelon configuration, our experimental setup did not always allow us to optimise the position of rider 3, namely for low yaw angle crosswinds. For this reason, riders 2 and 3 are not always placed to follow the best configuration, as identified in the previous section with 2 riders. This explains why the drag and lateral forces (as a percentage of those of an isolated rider) observed for rider 3 are sometimes higher than the values highlighted previously for rider 2 in a two-rider configuration. For instance, at 5° yaw the drag of rider 3 is 65% of the drag referred to a single cyclist (Fig. 9a), whereas, in the best configuration for two riders, the experienced drag is about 50% (Table 2). Nevertheless, for the yaw angles larger than 20° , the setup provides values consistent with those found in the two-rider analysis.

The analysis of the critical 30° yaw angle showed that the rider 4 needs to keep very close to the rider 3 to benefit of the protection from the lateral wind since a small increase (of about 0.75–1 m) in this distance induces an abrupt increase of the drag and lateral forces. This results can suitably help the cycling teams to plan race strategies allowing, for instance, to create a small gap between the guttered and the sheltered riders quite enough to promote the formation of a breakaway [e.g., 11].

5 Conclusions

In road race cycling, the crosswind substantially impacts the races and leads to splits in the peloton when echelons are formed by the riders of professional teams. Professional cyclists and practical cycling experts know that a rider finding himself in the disadvantaging position of the guttered rider behind the echelon has to struggle against the crosswind and is very likely to get dropped.

As far as we know, crosswind aerodynamics for groups of cyclists including echelons had not yet been studied. After focusing on an isolated cyclist and on two riders under crosswind conditions, this paper therefore aims at emphasising the distribution of aerodynamic drag and lateral forces in an echelon and comparing the forces experienced by a well-sheltered rider in the group and the guttered rider behind the echelon. Wind-tunnel measurements were carried out on model cyclists with a Reynolds

number which is approximately ten times lower than that of a full scale cyclist in real race conditions.

As a first step, we have therefore compared our measurements for a solo rider with the results presented by Fintelman et al. [17] (corresponding to a real scale cyclist). We observed a good consistency both with the experimental values and the numerical solutions, namely when $k - \epsilon$ turbulence model was employed. This agreement however does not allow us to jump to conclusions on the dependence of C_x and C_y on Re and to consider our experimental data as representative of real race conditions. Despite this, this general agreement shows that the dependence of C_x and C_y on the Reynolds number is relatively moderate in the range $4.5 \times 10^4 < Re < 5.0 \times 10^5$, in the sense that it is lower than the dependence of both coefficients on the wind incident angle α_y (the parameter on which this study aims in focusing at).

Different configurations were then tested with two riders under several crosswind conditions. We observed that specific configurations determine a significant reduction of the drag and lateral force for the sheltered rider with respect to an isolated cyclist.

Finally, an echelon configuration with 4 riders for varying yaw angle was investigated. It was found that the position of the guttered rider really becomes disadvantaging in terms of both drag and lateral force only beyond a 30° yaw, whereas in the same crosswind conditions a sheltered rider in the echelon benefits from even larger drag and lateral force reductions. An echelon is consequently worth being adopted by a cycling team only beyond 30° yaw angles. At 50° yaw, the guttered rider experiences a 3.4 times larger drag and a 4.9 times larger lateral force than the most sheltered rider of the echelon. Such a significant difference of forces might explain why in this situation it is so hard for the guttered cyclist to stick to the front group.

Furthermore, at a critical yaw angle around 30° , the guttered rider remains well sheltered but their position is very unstable, as they are very likely to get dropped if their wheel-to-wheel distance with the rider right in front is increased slightly. Their drag and lateral forces increase by a factor of 2 when this wheel-to-wheel distance increases from 10 cm to 1 m.

We stress again that the approximations of the experimental design—cyclist model, perforated grid, coarse geometry—affected the results and, therefore, they should be mainly considered as preliminary. Nevertheless, this data set allowed us to identify some significant configurations that might be investigated more deeply in future studies. Furthermore, these results might provide useful information to improve cycling team strategies including the type of echelon worth forming following the crosswind direction in order to maximise the probability that an opponent behind the echelon gets dropped.

The study was limited to small echelons with 4 riders. Further researches should focus on more complex echelons such as double or triple echelons which are formed in crosswind conditions (Fig. 1b). The reduction of the drag and lateral force might hence be different for the riders located at the bottom of these larger groups. The evaluation of aerodynamic effects (e.g. the potential reduction of the drag) on the leading riders of the peloton due to echelons in different crosswind conditions is also a subject that deserves to be investigated. It could also be interesting to study unsteady crosswind flows. In strong crosswind conditions, cyclists are subjected to wind gusts and as a result of that drag and lateral forces can fluctuate in a short time interval. Furthermore, future researches should investigate crosswind aerodynamics and echelons with CFD simulations. Notably, this would allow one to have an insight of the flow separation around a cyclist and study pressure and velocity fields within an echelon as performed by Blocken et al. [6] for a peloton under wind-free conditions or Fintelman et al. [17] for a solo rider under crosswind conditions.

Compliance with ethical standards

Conflict of interest The authors state that there is no conflict of interest.

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