Numerical study on the aerodynamic drag of drafting cyclist groups

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Abstract

This paper presents a Computational Fluid Dynamics (CFD) investigation of the aerodynamic effects of drafting in cycling. In drafting, cyclists ride close behind each other to reduce aerodynamic drag. The CFD simulations for single cyclists and for a group of two cyclists are successfully compared with wind-tunnel measurements. Both CFD simulations and wind tunnel measurements show that also the leading cyclist experiences a drag reduction, which goes up to 3.1% for groups of four cyclists and more. For six or more similarly-sized cyclists riding closely behind each other, the position enjoying the largest drag reduction is the one-but-last position.

1 Introduction

At racing speeds (about 54 km/h or 15 m/s in time trails), the aerodynamic resistance or drag is about 90% of the total resistance (Kyle & Burke, 1984; Lukes et al., 2005). Most previously published studies on cycling aerodynamics aimed at reducing the aerodynamic drag of a single cyclist. Fewer publications have addressed the drag reduction due to drafting. In drafting, two or more cyclists ride close behind each other to reduce aerodynamic drag. The few published studies on drafting all confirm the large drag reduction for the trailing riders (up to 30-40%), whereas there seems to be a lack of consensus about the effect of drafting on the leading rider. In this respect, Olds (1998) stated:

"It has been suggested that riding close behind a leading cyclist will also assist the leading rider in that the low pressure area behind the cyclist will be "filled up" by the trailing rider. However, both Kyle (1979) and McCole et al. (1990) failed to find any measurable effect either in rolldown experiments or in field VO_2 measurements."

On the other hand, Computational Fluid Dynamics (CFD) studies on human body models with simplified geometries (such as elliptical cylinders) found drag reductions for the leading cylinder up to 5% (Iniguez-de-la-Torre and Iniguez, 2009). This study presents detailed 3D CFD simulations of drafting cyclists based on realistic human body geometries. Such 3D CFD simulations were the focus of this new study, which included also wind-tunnel measurements. First, the wind-tunnel measurements were used for CFD validation for single cyclists and two drafting cyclists. Next, supported by the validation study, CFD simulations were performed for groups up to eight drafting cyclists, allowing assessment of aerodynamic drag at every position in the group.

2 Wind-tunnel measurements

Two sets of wind-tunnel measurements are used. The first set included overall drag force measurements as well as point measurements with 30 pressure plates on the body of a real cyclist (Cyclist A: height 1.83 m, weight 72 kg) in different positions, including the upright position (UP), the dropped position (DP) with straight arms and the time-trial position (TTP) (Fig. 1). The second set consisted of overall drag force measurements on two drafting cyclists (Cyclists B and C) behind each other at a wheel-to-wheel separation distance d = 0.15 m. In all measurements, the wheels and legs were static (i.e., no pedalling). A conservative estimate of the measurement error of the drag force is 0.3% at an approach-flow air speed of U_∞ = 15 m/s. The measurement results are reported together with the CFD results in the next sections.

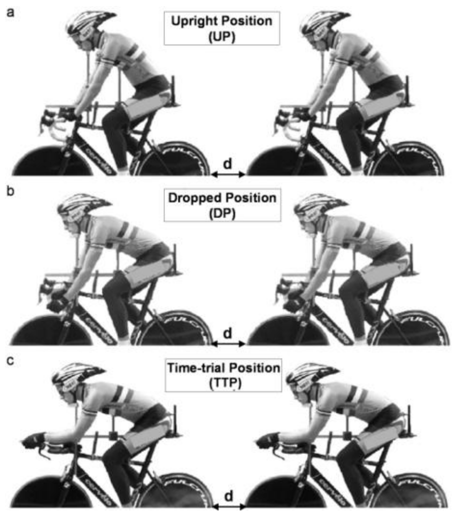

Figure 1: Three cycling positions with indication of bicycle separation distance d (wheel-to-wheel): (a) Upright position (UP); (b) Dropped position (DP) with straight arms; (c) Time-trial position (TTP).

3 Computational models

Digital models of the cyclist (Cyclist A) were obtained with high-resolution 3D laser scanning. To generate groups of up to eight riders, the cyclist geometry (only cyclist body, not bicycle) was copied and the cyclists were placed behind each other with a wheel-to-wheel separation distance d = 0.01 m. The cyclists were placed in a computational domain with dimensions and spatial discretisation according to best practice guidelines in CFD and based on grid-sensitivity analysis (Casey & Wintergerste, 2000; Franke et al., 2007; Tominaga et al., 2008) (Fig. 2). Very small control volumes of 30 μm were applied at the cyclist body surface to resolve the boundary layer down to the thin viscous sublayer (Fig. 2b). This is important because boundary-layer separation determines to a large extent the aerodynamic drag. Further away from the surface, tetrahedral cells were used with an average size of about 0.03 m. The grids for the single cyclist contained about 7.7×10^6 cells versus 35.6 $\times 10^6$ cells for the eight drafting cyclists. The simulations were made with a uniform inlet velocity of 15 m/s and a turbulence intensity of 0.02% as in the wind tunnel, representing the relative air movement when cycling at this velocity in still air (zero wind speed). The 3D steady Reynolds-averaged Navier-Stokes (RANS) equations were solved with the standard k-ε turbulence model, near-wall modelling with the one-equation Wolfshtein model, pressure-velocity coupling with the SIMPLE algorithm, second-order pressure interpolation and second-order discretisation schemes using the commercial CFD code ANSYS/Fluent 12. Convergence was monitored carefully and the iterations were terminated when all residuals showed no further reduction with increasing number of iterations.

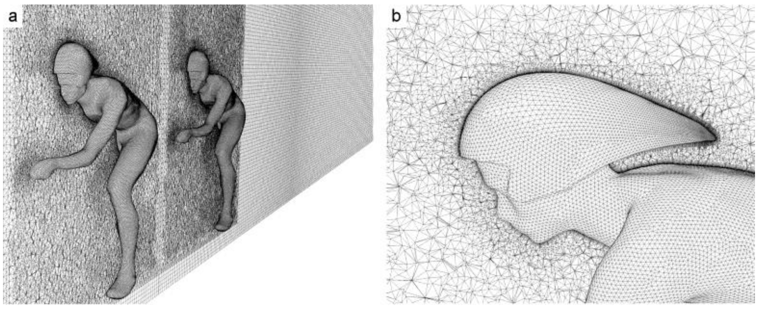

Figure 2: (a) Grid for two drafting cyclists in time-trial position and with bicycle separation distance *d* = 0.01 m. (b) Detailed view of computational grid near upper body, head and helmet.

4 CFD simulations versus wind-tunnel measurements

The CFD simulations only consider the body of the cyclist. Therefore, the corresponding experimental drag area of the cyclist body is obtained by subtracting the experimental drag area of the bicycle configuration plus force platform, which was measured separately, from the total experimental drag area of the cyclist body, bicycle and platform. The deviations between CFD simulations and measurements are 10.5%, 3.5% and 0.7% for the UP, DP and TTP, respectively. Given the very low percentage deviation for TTP, it is likely that some errors have cancelled each other. Similar simulations were made for the two drafting cyclists in DP at d = 0.15 m, yielding a drag reduction for the leading cyclist of 1.3% versus 1.6% from the wind-tunnel measurements. Both the CFD simulations and the wind-tunnel measurements confirm the drag reduction of the leading rider due to the presence of a trailing rider in his wake. The agreement between the CFD simulations and the wind-tunnel measurements is considered to be very good, which justifies using these simulations for further analysis of the flow field and also using the same computational models (grid, turbulence model, etc.) for the CFD simulations of groups of up to eight drafting cyclists. The full paper will present a detailed flow-field analysis for two drafting cyclists, with extrapolation to larger groups.

5 Drag reductions for groups of drafting cyclists

Because the aerodynamic drag of a leading cyclist is significantly reduced by a trailing cyclist in his wake, it can be expected that in larger groups of cyclists, the largest drag reduction is not experienced by the last cyclist – as is generally assumed – but by the one-but-last cyclist. Indeed, while the last cyclist benefits from the leading riders in front of him, the one-but-last cyclist benefits from both the riders in front of him and the rider behind him. This is confirmed by the CFD simulations: Figure 3 shows the drag reduction for every cyclist in a group of two, four, six or eight riders. For groups of six or more similarly-sized riders, the one-but-last rider experiences the largest drag reduction. For smaller groups, it is the last rider that has the largest drag reduction. The reason is that the wake behind the riders widens with downstream position. Therefore, as an example, the last rider in a group of three benefits more than the last one in a group of two. The widening of the wake becomes less pronounced from about the fifth position, and the beneficial effect of having a trailing rider in your wake then becomes comparatively more important. In addition, note that the leading cyclist in a team of three or more experiences a larger benefit (3.1%) than in a team of two (2.6%), due to the upstream disturbance of the flow (overpressure area) by the third rider that extends up to the position of the first.

6 Discussion and conclusions

The two main limitations of the study are, first, that all cyclists had identical body geometry and position on the bicycle, and second, that only static positions (i.e., no pedalling) were evaluated, without the bicycle(s). The simulations were also performed for cyclists directly behind each other at a separation distance of only 0.01 m. While this distance is unrealistically low when riding precisely behind each other, it should be noted that cyclists often ride much closer to each other, be it in a slightly staggered arrangement, with the front wheel of the trailing rider next to the back wheel of the leading rider. Future work will include analysis of drag effects in such arrangements.

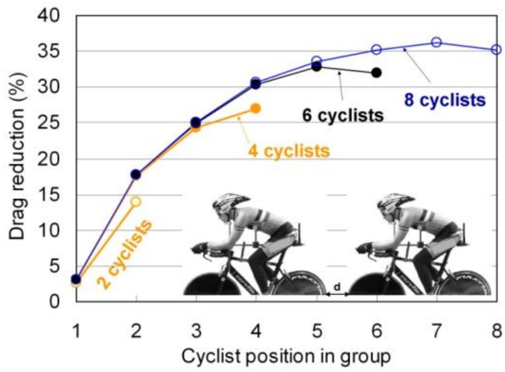

Figure 3. Numerically simulated drag reduction in groups of 2, 4, 6 and 8 cyclists, in time-trial position with bicycle separation distance *d* = 0.01 m.

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