Impact of a motorcycle on cyclist aerodynamic drag in parallel and staggered arrangements

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Abstract

Cycling races contain a multitude of motorcycles for various activities including television broadcasting. During parts of the race, these motorcycles can ride in close proximity of cyclists. Earlier studies focused on the impact of a nearby motorcycle on cyclist drag for in-line arrangements. It was shown that not only a motorcycle in front of a cyclist but also a motorcycle closely behind a cyclist can substantially reduce cyclist drag. However, there appears to be no information in the scientific literature about the impact of the motorcycle on cyclist drag for parallel and staggered arrangements. This paper presents wind tunnel measurements of cyclist drag for 32 different parallel and staggered cyclist-motorcycle arrangements. It is shown that the parallel arrangement leads to a drag increase for the cyclist, in the range of 5 to about 10% for a lateral distance of 2 to 1 m. The staggered arrangement can lead to either a drag increase or a drag decrease, where the latter is about 2% for most positions analyzed. For one of the parallel arrangements, computational fluid dynamics simulations were performed to provide insight into the reasons for the drag increase. A cyclist power model was used to convert the drag changes into potential time gains or losses. Compared to a lone cyclist riding at a speed of 46.8 km/h (13 m/s) on level road in calm weather, the time loss by a drag increase of 10%, 4% and –2% was 2.16, 0.76 s and –0.80 s per km, respectively. These time differences are large enough to influence the outcome of cycling races.

Keywords Computational fluid dynamics · Wind tunnel · Aerodynamic cyclist drag · Cycling aerodynamics · Motorbike

1 Introduction

The aerodynamic resistance or drag of a cyclist is about 90% of the total resistance at racing speeds of about 40 km/h (11.1 m/s) [1–3]. Much scientific research in professional cycling is therefore focused on the reduction of cyclist drag (e.g., [4, 5]). Cycling races contain a multitude of cars and motorcycles. The motorcycles can be neutral support, commissaire, traffic manager, information, doctor, police or press motorcycles, where the latter can be camera, sound or photographer motorcycles. The motorcycles are allowed to maneuver in the proximity of the cyclists when filming

or recording. Filming is only forbidden in the last 500 m of the race. Previous research analyzed the impact of nearby cars and motorcycles on cyclist drag. Blocken and Toparlar [6] determined that a car behind a cyclist can yield a drag reduction for the cyclist of 3.7, 1.4 and 0.2% for separation distances of 3, 5 and 10 m, respectively. Blocken et al. [7] demonstrated that a motorcycle following a cyclist can provide a drag reduction for the cyclist of 3.8, 0.3 and 0.1% for separation distances of 1, 5 and 10 m, respectively. More recently, Blocken et al. [8] focused on quantifying the aerodynamic benefits for a cyclist by drafting behind a motorcycle. While it was well known in professional cycling that drafting behind a motorcycle can yield large drag reductions, the actual values had not yet been determined. It was shown that drafting at 2.64, 10, 30 and 50 m behind a motorcycle could yield drag reductions of 48, 23, 12 and 7%, respectively.

At many occasions during a race, cyclists and motorcycles are not riding in line, but in parallel (Fig. 1a) or staggered arrangement (Fig. 1b–d). The pertaining guidelines of the International Cycling Union (UCI) for “vehicle circulation in

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Fig. 1 Photos of cyclist and motorcycle in parallel or staggered arrangement: (a) parallel; (b–d) staggered. (Fig. sources: a: mark Dadswell/Getty Images; b–d: Radu Razvan/Shutterstock.com; all photos reproduced with permission)

the race convoy” only stipulate when and which motorcycles can enter the gaps between breakaway riders and the following riders in terms of time differences, which can be 15, 30, 60 and 90 s [9]. The larger the time differences, the more motorcycles can enter the gap. However, the UCI guidelines do not specify what distance should be kept between the motorcycles and the cyclists [9].

To the best of our knowledge, there is no information in the scientific literature about the impact of a nearby motorcycle on cyclist drag for parallel and staggered arrangements. Some earlier studies assessed the aerodynamic interaction between two cyclists in parallel and staggered arrangement. Zdravkovich et al. [10] performed wind tunnel tests with real riders in a variety of in-line and slightly staggered arrangements. The slightly staggered arrangements were studied because they were considered safer as they reduce the chance of catching the rear wheel of the lead cyclist and provide a less obstructed view of the road ahead. It was found that the beneficial drafting effect was abruptly reduced for both a 0.2 and 0.3 m stagger. Barry et al. [11] conducted wind tunnel experiments on a real cyclist together with a manikin in both in-line and so-called overtaking positions, including a parallel arrangement. They described the variation of the drag during the overtaking process. As the overtaking rider moved forward, the leading rider drag

increased. When both riders were side by side, they both had a drag above that of an isolated rider. As the overtaking continued, a drag decrease occurred for both riders. For the side-by-side arrangement with a minimum lateral separation distance of 0.5 m between the two rider centerlines, the drag increase was 6%. This increase became negligible beyond 1.5 m lateral separation. More recently, Gromke and Ruck [12] performed a field measurement campaign assessing the lateral loads on cyclist dummies of an adult and a child being overtaken by a station wagon. Different bicycle types were considered and distinct lateral load phases were observed: a pressure phase with a lateral load acting to push the cyclist away followed by a suction phase with a lateral load acting to pull the cyclist towards the vehicle. They did not provide information on the aerodynamic drag in the riding direction, which is the focus of the present paper.

These studies on the aerodynamic effect of a nearby cyclist or a car on a cyclist provide some trends that could be expected to hold also for a cyclist and a nearby motorcycle. However, the streamwise and lateral distances between two drafting and overtaking cyclists are typically much smaller than those occurring between a cyclist and a motorcycle, necessitating a separate study for the latter. Therefore, this paper presents a series of wind tunnel measurements and some computational fluid dynamics (CFD) simulations to

analyze the impact of a nearby motorcycle on cyclist drag for parallel and staggered arrangements.

2 Wind tunnel experiments

2.1 Experimental set-up

The wind tunnel experiments (WT) were performed on quarter-scale models of a cyclist and a motorcycle carrying two people (Fig. 2a-d). Details of the models and the wind tunnel can be found in [8, 13]. The WT set-up was described in an earlier publication [8] and the description is summarized here for completeness. The models were placed on an elevated sharp-edged smooth horizontal plate to limit

boundary layer development. (Fig. 2e-f). The blockage ratio of the set-up was about 2%, which is below the recommended maximum of 5% for WT tests [14]. The measured longitudinal turbulence intensity at the model position was 0.3%. The cyclist was positioned on a force sensor that was situated below the plate. The force sensor was designed and manufactured in house specifically for high-accuracy quarter-scale cyclist WT tests [15] with an accuracy of 0.001 N. Data were sampled at 10 Hz for 60 s. Tests were performed at wind speeds of 15, 20, 25 and 30 m/s to detect Reynolds number independence, which was noted above 20 m/s. The Reynolds number independent results are reported in the results section. It was assumed that there was no crosswind, no head wind and no tail wind, therefore the WT speed represented the riding velocity.

Fig. 2 a, b Dimensions (full-scale equivalent) of the quarter-scale models. c, d Photos of wind tunnel set-up: cyclist and motorcycle in (c) parallel or (d) staggered position. e, f Cyclist and motorcycle in

staggered position on elevated sharp-edged plate with reduced-scale dimensions in mm: (e) Side view; (f) Front view

Two sets of cyclist-motorcycle arrangements were tested. All distances below are reported in full-scale values. The first set of 27 arrangements had the motorcycle at a lateral distance $\Delta y = 1.3$ m and a streamwise distance Δx ranging from +7.2 m (cyclist downstream of motorcycle) to -4.8 m (cyclist upstream of motorcycle) in steps of 0.48 m (Fig. 3). The second set of five arrangements had the cyclist and motorcycle parallel (both front wheel ends at same streamwise coordinate) and Δy ranging from 1 to 2 m in steps of 0.25 m (Fig. 4). To assess the repeatability of the experimentally obtained drag values, the isolated cyclist was tested five times throughout the measurement campaign, by detaching and remounting the model on the force sensor. Based on these measurements, the repeatability of the obtained drag values was found to be 0.7–0.9%, which corresponded to drag differences of about 0.3 N for the isolated cyclist. All

drag measurements were corrected to match the following reference values: 101,325 Pa (standard atmosphere), 15 °C, 15 m/s (a top time trial speed) and full geometrical scale.

2.2 Results

Figure 3 presents the results for the first WT set. The parallel position yielded an increase of cyclist drag of about 7.5%. This drag increase lowered as the cyclist and motorcycle move farther apart in the streamwise direction. For the cyclist upstream of the motorcycle, at $\Delta x = -1.44$ m, the drag change was nearly zero and switched sign. For larger distances, the cyclist experienced a drag decrease until about $\Delta x = -4.8$ m. This drag decrease was attributed to the so-called subsonic upstream disturbance similar to earlier studies [6, 7, 16]. This refers to the fact that the

Fig. 3 Drag change in percentage for cyclist due to proximity of motorcycle, for fixed lateral distance $\Delta y = 1.3$ m (full scale) and varying streamwise distance Δx (full scale)

Fig. 4 Drag increase in percentage for cyclist due to proximity of motorcycle in parallel arrangement for varying lateral distance Δy (full scale)

motorcycle — just like the cyclist — does not only disturb the flow downstream but also upstream of it. For the cyclist downstream of the motorcycle, a drag decrease occurred from about $\Delta x = +1.92$ m to at least $+7.2$ m. This could be attributed to the partial presence of the cyclist in the wake behind the motorcycle. Figure 4 shows the results for the second WT set. The drag increase of the parallel arrangement gradually became less pronounced as Δy increased, but still amounted to 5% at $\Delta y = 2$ m. To provide further insight in the reasons of these drag differences, some CFD simulations were performed.

3 CFD simulations

3.1 Computational settings and parameters

The CFD simulations were performed at full scale. The cyclist and motorcycle geometry were identical to those of the WT models apart from the WT model bottom plate, the vertical reinforcement bars in the cycling wheels (Fig. 2c-d) and the geometrical scale (1:1 versus 1:4). Δy was 1.3 m. The rectangular computational domain had dimensions length $\times$ width $\times$ height = $60 \times 32 \times 24$ m³. The blockage ratio was about 0.1%, which is below the recommended maximum of 3% for CFD simulations [17–20].

The computational grids were hybrid hexahedral–tetrahedral grids based on grid convergence analysis (not reported here) and on grid generation guidelines [16–24]. They had a

wall-adjacent cell size of $20 \mu\text{m}$ ($=0.02$ mm) and 40 layers of prismatic cells near the cyclist and motorcycle surfaces to accurately resolve the thin boundary layer including the laminar sublayer (Fig. 5). The dimensionless wall unit y^+ had values that were generally below one and always below five. The cell size in the area between motorcycle and cyclist was 0.03 m. Figure 5 shows the grid resolution on the surface of the cyclist, motorcycle and in the vertical plane through the cyclist. The total cell count was 53.2×10^6 .

The computational settings are identical to those in [8] and are summarized here for completeness. At the inlet, a uniform velocity of 15 m/s was imposed that represented the riding velocity. As in the WT tests, it was assumed that there was no crosswind, no head wind and no tail wind. The inlet turbulence intensity was set to 0.5% to obtain the same approach-flow value of 0.3% in the region directly upstream of the motorcycle as in the wind tunnel. This was required because the turbulence intensity decayed from 0.5 to 0.3% from the inlet of the computational domain to the position of the motorcycle model. At the outlet, zero static gauge pressure was set. The bottom, side and top surfaces of the domain were slip walls. The surfaces of the motorcycle and cyclist were no-slip walls, where the cyclist body and the motorcycle had a surface roughness with equivalent sand-grain roughness height $k_s = 0.1$ mm and the bicycle $k_s = 0$ mm.

Scale Adaptive Simulations (SAS) [26] were performed involving the Shear Stress Transport (SST) $k-\omega$ model [25] with curvature correction. Pressure–velocity coupling was

Fig. 5 Computational grid on motorcycle and cyclist surfaces and in vertical centerplane for streamwise distance $\Delta x = 0$ and lateral distance $\Delta y = 1.3$ m. Minimum cell size: 0.02 mm (full scale). Total cell count is 53.2 million

performed by the PISO algorithm. Pressure interpolation was second order, gradient interpolation was conducted with the Green–Gauss node-based scheme. Bounded central differencing was used for the momentum equations and second-order discretization for the turbulence model equations. Time discretization was bounded second-order implicit. The simulations were performed with the commercial CFD code Ansys Fluent 16.1 [27]. The time step of 0.002 s was selected such that the Courant–Friedrichs–Lewy (CFL) number was equal to unity or below unity in the area between the motorcycle and the cyclist. A time step convergence analysis confirmed the suitability of this time step [8]. The number of time steps required to obtain a constant moving average of the sampled drag values was 8000.

3.2 Results

The computed isolated cyclist drag area (C_dA) was 0.231 m² while that of the cyclist in parallel arrangement with the motorcycle was 0.248 m², yielding about 7.5% drag increase, in line with the WT result at $\Delta x = 0$ (Fig. 3).

Figure 6 presents contours of air speed in a horizontal plane at 0.8 m above ground, for the parallel arrangement compared with the isolated cyclist. Figure 6a,b shows the time-averaged results, while Fig. 6c–j shows instantaneous results at time intervals of 0.12 s. The presence of the motorcycle increased the size of the high-speed areas (red color) wrapping around the cyclist's waist. These areas partly interacted with similar areas around the front part of the motorcycle, yielding a high-speed jet in between the cyclist and motorcycle (see Fig. 6a). Due to the presence of the motorcycle, the velocity in the wake behind the cyclist increased, the wake behind the cyclist widened and slightly curved towards the wake behind the motorcycle.

Figure 7 depicts contours of pressure coefficient C_p in a horizontal plane at 0.8 m above ground. For the isolated cyclist, a clear over-pressure area (red/orange) in front and under-pressure areas (blue) on the side and behind the cyclist body were present, where the latter was distorted over time by periodic vortex shedding. For the parallel arrangement, the large over-pressure area in front of the motorcycle partly merged with that in front of the cyclist. Also the large under-pressure area behind the motorcycle partly merged with that behind the cyclist. As a result, the size of the most intense under-pressure areas wrapping around the waist of the cyclist increased substantially, as did the size of the under-pressure area behind the cyclist and the overall absolute value of the pressure coefficient in the wake behind the cyclist. The larger under-pressure areas on the side were in line with the faster air speed around the sides of the cyclist in Fig. 6.

Figure 8 displays contours of mean C_p on the surface of the cyclist and motorcycle. While Fig. 8a,b only shows minor differences in terms of the positive C_p values, Fig. 8c–f clearly

shows larger under-pressure on the sides and torso of the cyclist as well as on the bicycle rear wheel due to the presence of the motorcycle.

Animations of the SAS-SST $k-\omega$ simulations are provided in (Supplementary Material 1, 2, 3, 4).

4 Potential time gains

The road cycling power model by Martin et al. [28] was employed to convert the drag change percentages in Figs. 3 and 4 to potential speed changes and potential time gains or losses:

$$P_{\text{tot}} = (P_{\text{ad}} + P_{\text{rr}} + P_{\text{wb}} + P_{\text{pe}} + P_{\text{ke}}) \left(\frac{1}{\eta} \right) \quad (1)$$

With P_{tot} the required power, P_{ad} the power loss due to aerodynamic drag, P_{rr} the power loss due to rolling resistance, P_{wb} the power loss due to friction in the wheel bearings, P_{pe} the power changes due to a change in potential energy and P_{ke} the power changes due to changes in kinetic energy. The efficiency η is that of the cyclist power transmission, associated to the friction in the drivetrain. For simplicity, we assumed level terrain and constant cycling speed so $P_{\text{pe}} = P_{\text{ke}} = 0$, and no crosswind, headwind or tailwind. Equation (1) then becomes [28]:

$$P_{\text{tot}} = [0.5\rho U^3 (C_D A + F_w) + UC_{rr}mg + U(91 + 8.7U) \cdot 10^{-3}] \frac{1}{\eta} \quad (2)$$

We assumed the following parameter values: density $\rho = 1.225 \text{ kg/m}^3$, reference isolated cyclist riding velocity $U = 13 \text{ m/s}$, drag area $C_D A = 0.231 \text{ m}^2$, wheel rotational drag area $F_w = 0.001 \text{ m}^2$, rolling resistance coefficient $C_{rr} = 0.002$, cyclist-bicycle system mass $m = 75 \text{ kg}$, gravitational constant $g = 9.81 \text{ m/s}^2$ and chain efficiency $\eta = 0.97698$. Note that 13 m/s was chosen instead of 15 m/s as a more common speed for an isolated professional cyclist. This slight change in speed is expected not to influence the findings as the associated Reynolds effects on the percentages in Figs. 3, 4 are very limited. These values lead to $P_{\text{tot}} = 342 \text{ W}$ for the isolated cyclist riding at 13 m/s. To relate drag changes to speed changes and time gains or losses, it was assumed that the cyclist provided the same power $P_{\text{tot}} (= 342 \text{ W})$ when accompanied by the motorcycle. Table 1 presents the associated speed changes and the potential time gain or loss per km and per minute.

5 Discussion

The results of the CFD simulations can explain the drag changes in Figs. 3 and 4. Figure 3 shows an increased cyclist drag for parallel and slightly staggered

Fig. 6 Results of SAS simulations for cyclist and motorcycle in parallel (left) versus isolated cyclist (right): contours of air speed in horizontal plane at 0.8 m height: (a, b) mean; (c–j) instantaneous at 0.12 s intervals

Fig. 7 Results of SAS simulations for cyclist and motorcycle in parallel versus isolated cyclist: contours of pressure coefficient C_p in horizontal plane at 0.8 m height: (a–b) mean; (c–j) instantaneous at 0.12 s intervals

arrangements. Figures 6 and 8 show that the motorcycle increased the speed increment around the cyclist and the suction on the back of the cyclist. For the cyclist upstream

of the motorcycle for $\Delta x = -1.92$ m and further, the cyclist experienced a drag decrease due to the subsonic upstream disturbance: the over-pressure area in front of

Fig. 8 Results of SAS simulations: contours of mean pressure coefficient C_p on the surfaces of cyclist and motorcycle, for the parallel arrangement versus the isolated cyclist

the motorcycle partly merged with the under-pressure area behind the cyclist, which reduced the suction on the back of the cyclist [6, 7, 16]. For the cyclist downstream of the motorcycle, for $\Delta x = 1.92$ m and more, the cyclist experienced a drag decrease. This drag decrease occurred because the cyclist was partly positioned in the wake behind the motorcycle, which widened with increasing distance downstream, while simultaneously the velocity in the wake increased. These two effects seemed to balance

each other yielding a fairly constant cyclist drag reduction from $\Delta x = +2.88$ up to at least $+7.2$ m. Figure 4 shows a gradual reduction of the increased cyclist drag for larger Δy . This is attributed to the reduced effect of the motorcycle on the air speed around the cyclist and suction on the cyclist's back with increasing Δy .

Table 1 indicates that the potential time gains or losses are large, even for the moderate drag changes of about 2%. As time

Table 1 Potential changes in speed and time as a function of the change in drag

Drag change	Speed change	Time change per km	Time change per min
(%)	(%)	(s)	(s)
12	−3.6	−2.88	−2.16
10	−3.1	−2.41	−1.82
8	−2.5	−1.94	−1.48
6	−1.8	−1.47	−1.12
4	−1.2	−0.98	−0.76
2	−0.6	−0.49	−0.38
0	0.0	0	0
−2	0.7	0.50	0.39
−4	1.3	1.01	0.80

trials are sometimes won by fractions of a second, it is clear that a nearby motorcycle can influence the outcome of races.

Note that the precise values of drag reduction and time gains or losses in this paper pertain to the specific cyclist and motorcycle geometry tested and the parameter values chosen in Sect. 4. Crosswind, head wind or tail wind will evidently influence the drag and speed changes and the potential time gains and losses. When crosswind is present, the aerodynamic interaction between the cyclist and the motorcycle will be much more complicated and further research is required to study the associated wide range of possible scenarios.

Combined with our previous work on the aerodynamic impact of a nearby motorcycle on cyclist drag [7, 8], we now have a strong overall picture of the effect of a motorcycle, which can be in front, behind or to the side, on the aerodynamic drag of a cyclist. Each of these motorcycle positions has a clear effect that can change the outcome of a race. The present rules and guidelines of the UCI do not prevent these aerodynamic effects of nearby motorcycles. The most recent guidelines for “vehicle circulation in the race convoy” [9] only stipulate when and which motorcycles can enter the gaps between breakaway riders and the following riders in terms of time differences. Therefore, the UCI should consider modifying their rules and guidelines to prevent these undesired and unfair aerodynamic impacts. Nevertheless, solutions might not be straightforward given the wide range of duties of in-race motorcycles. A partial and potential solution could be the use of drones for television recording, to reduce the number of motorcycles in the race convoy to a minimum.

6 Conclusion

Building on our previous work that quantified the effect of a leading or trailing motorcycle on the drag of a cyclist, this paper analyzed the effect of a motorcycle in parallel

and staggered arrangements with the cyclist. Wind tunnel tests for 32 different parallel and staggered cyclist-motorcycle arrangements were presented. It was shown that the parallel position leads to a substantial drag increase for the cyclist, in the range of 5 to about 10% for a lateral distance of 2 to 1 m. The staggered position can lead to either a large drag increase or a moderate drag decrease of about 2% for most positions analyzed. For one of the parallel arrangements, CFD simulations were performed to provide insight in the reasons for the large drag increase. A cyclist power model was used to convert the drag changes into potential time gains or losses. Compared to a lone cyclist at 46.8 km/h (13 m/s) on a level road in calm weather, the time loss by a drag increase of 10%, 4% and −2% was 2.16, 0.76 s and −0.80 s per km, respectively. These time differences are large enough to influence the outcome of cycling races.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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References

1. Kyle CR, Burke ER (1984) Improving the racing bicycle. *Mech-Eng* 1:34–45

2. Grappe F, Candau R, Belli A, Rouillon JD (1997) Aerodynamic drag in field cycling. *Ergonomics* 40:1299–1311
3. Lukes RA, Chin SB, Haake SJ (2005) The understanding and development of cycling aerodynamics. *Sport Eng* 8:59–74
4. Crouch TN, Burton D, LaBry ZA, Blair KB (2017) Riding against the wind: a review of competition cycling aerodynamics. *Sport Eng* 20:81–110
5. Malizia F, Blocken B (2020) Bicycle aerodynamics: history, state of the art and future perspectives. *J Wind EngIndAerodyn* 200:104134
6. Blocken B, Toparlar Y (2015) A following car influences cyclist drag: CFD simulations and wind tunnel measurements. *J Wind EngIndAerodyn* 145:178–186
7. Blocken B, Toparlar Y, Andrianne T (2016) Aerodynamic benefit for a cyclist by a following motorcycle. *J Wind EngIndAerodyn* 155:1–10
8. Blocken B, Malizia F, van Druenen T, Gillmeier SG (2020) Aerodynamic benefit for a cyclist by drafting behind a motorcycle. *Sports Eng* 23:19
9. International Cycling Union (2017) Guidelines for vehicle circulation in the race convoy. Version February 2017. www.uci.org/inside-uci/publications
10. Zdravkovich MM, Ashcroft MW, Chisholm SJ, Hicks N (1996) Effect of cyclist's posture and vicinity of another cyclist on aerodynamic drag. *The Engineering of Sport* (Haake (Ed.)), 21–28, Balkema, Rotterdam.
11. Barry N, Sheridan J, Burton D, Brown NAT (2014) The effect of spatial position on the aerodynamic interactions between cyclists. *ProcEng* 72:774–779
12. Gromke C, Ruck B (2021) Passenger car-induced lateral aerodynamic loads on cyclists during overtaking. *J Wind EngIndAerodyn* 209:104489
13. Eindhoven University of Technology (2017) You Tube channel; wind tunnel movie: https://www.youtube.com/watch?v=VEDn_IUJQfs
14. Barlow JB, Rae WH, Pope A (1999) Low-speed wind tunnel testing. John Wiley and Sons
15. Blocken B, van Druenen T TY, Malizia F, Mannion P, Andrianne T, Marchal T, Maas GJ, Diepens J (2018) Aerodynamic drag in cycling pelotons: new insights by CFD simulation and wind tunnel testing. *J Wind EngIndAerodyn* 179:319–337
16. Blocken B, Defraeye J, Koninckx E, Carmeliet J, Hespel P (2013) CFD simulations of the aerodynamic drag of two drafting cyclists. *Comput Fluids* 71:435–445
17. Franke J, Hirsch C, Jensen AG, Krüs HW, Schatzmann M, Westbury PS, Miles SD, Wisse JA, Wright NG (2004) Recommendations on the use of CFD in wind engineering. *Proc. Int. Conf. Urban Wind Engineering and Building Aerodynamics*, (Ed. van Beeck JPAJ), COST Action C14, Impact of Wind and Storm on City Life Built Environment, von Karman Institute, Sint-Geneisius-Rode, Belgium, pp. 5–7
18. Franke J, Hellsten A, Schlünzen H, Carissimo B (2007) Best practice guideline for the CFD simulation of flows in the urban environment. *COST Action* 5:732
19. Tominaga Y, Mochida A, Yoshie R, Kataoka H, Nozu T, Yoshikawa M, Shirasawa T (2008) AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings. *J Wind EngIndAerodyn* 96:1749–1761
20. Blocken B (2015) Computational Fluid Dynamics for urban physics: Importance, scales, possibilities, limitations and ten tips and tricks towards accurate and reliable simulations. *Build Environ* 91:219–245
21. Malizia F, Blocken B (2020) CFD simulations of an isolated cycling spoked wheel: impact of the ground and wheel/ground modeling. *Eur J Mech B Fluids* 82:21–38
22. Casey M, Wintergerste T (2000) Best practice guidelines ERCOFTAC special interest. ERCOFTAC
23. Tucker P, Mosquera A (2001) NAFEMS introduction to grid and mesh generation for CFD. NAFEMS CFD Work. Group.
24. Malizia F, Montazeri H, Blocken B (2019) CFD simulations of spoked wheel aerodynamics in cycling: impact of computational parameters. *J Wind EngIndAerodyn* 194:103988
25. Menter FR (1994) Two-equation eddy-viscosity turbulence models for engineering applications. *AIAA J* 32(8):1598–1605
26. Menter F, Egorov Y (2010) The scale-adaptive simulation method for unsteady turbulent flow predictions. Part 1: theory and model description. *Flow Turb Combust* 85:113–138
27. ANSYS Inc (2015) Ansys Fluent Theory Guide, Release 16.1. Canonsburg
28. Martin JC, Milliken DL, Cobb JE, McFadden KL, Coggan AR (1998) Validation of a mathematical model for road cycling. *J ApplBiomech* 14:276–291

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