Aerodynamic drag in cycling team time trials

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\textbf{A R T I C L E  I N F O}

\textbf{Keywords:}
Team time trial
Computational fluid dynamics
Numerical simulation
Wind tunnel
Aerodynamic cyclist drag
Cycling aerodynamics

\textbf{A B S T R A C T}

In a team time trial (TTT), the main strategy is based on drafting, where team members alternate take the lead while others ride behind the leading cyclist. TTTs can contain up to 9 riders of the same team. To the best of our knowledge, systematic aerodynamic studies of drafting groups from 2 up to 9 riders have not yet been published. Therefore, this paper presents such an analysis for up to 9 drafting cyclists in a single paceline, with wheel-to-wheel spacings $d = 0.05, 0.15, 0.5, 1$ and $5$ m. A total of 47 Computational Fluid Dynamics (CFD) simulations are performed with the 3D RANS equations, standard $k$-$\varepsilon$ model and scalable wall functions and validated with wind-tunnel measurements. In groups of up to 5 identical riders with $d$ up to $1$ m, the last rider has the lowest drag but this is not the case for larger groups. A closely drafting group of 7, 8 or 9 riders has an average drag that is about half that of an isolated rider. However, for much longer theoretical single pacelines, a staggered peloton configuration can yet be about two times more drag efficient.

\textbf{1. Introduction}

A team time trial (TTT) is a road cycling race in which cyclists of the same team race together as a group against the clock in a competition with other teams. The main strategy in TTTs is based on drafting, where team members alternate in taking the lead (also called: taking a pull) while others take advantage of the slipstream behind the leading rider(s). This allows the drafting riders to recover while the leading rider is overcoming the largest air resistance. After his or her turn, the leading rider will move away in lateral direction and towards the back in riding direction, allowing the second rider to take the lead. The leading rider will generally get back in line at the very end of the formation. As such, the TTT group rotates and every rider gets to take the pull for a certain duration, and this process is repeated many times during a typical TTT. Typical TTTs can contain from 2 up to 9 riders. Two of the most popular configurations are the single paceline and the circular paceline. Examples of the single paceline in competitive TTTs are shown in Fig. 1. Typically, the recorded finishing time will be the time of the $n$-th rider of the team, where $n$ is smaller than the total number of riders. For example, for TTT teams of 8 or 9 riders, often the time at which the 4th rider crosses the finish line is taken as the time of the team and this time is awarded to all 4 riders that finished first, while the other riders – if they come later – will be given their actual finishing time. TTT strategy might include “dropping” the least performing riders towards the end of the race and aiming at getting the best possible time for the first four riders and hence to win the TTT.

It is well-known that the greatest potential for improvement in cycling speed is situated in its aerodynamics (Wilson, 2004). At professional racing speeds (about 54 km/h or 15 m/s), the aerodynamic resistance or drag is about 90% of the total resistance (Kyle and Burke, 1984; Grappe et al., 1997; Lakes et al., 2005). Therefore, reducing the aerodynamic resistance of every rider but also of the group as a whole is of paramount importance for a successful TTT. Aerodynamic drag in cycling can be assessed by field tests, wind tunnel measurements and numerical simulation by Computational Fluid Dynamics (CFD). The use of CFD in wind engineering, also referred to as Computational Wind Engineering, has seen a rapid growth in the past 50 years (Murakami, 1997; Stathopoulos, 1997; Baker, 2007; Tomimaga and Stathopoulos, 2013, 2016; Meroney and Derickson, 2014; Blocken, 2014, 2015, 2018; Meroney, 2016). As part of wind engineering, also the field of cycling aerodynamics has adopted the use of CFD (Blocken, 2014; Crouch et al., 2017).

Most previous studies on cycling aerodynamics focused on the drag of a single (isolated) cyclist (e.g. Kyle and Burke, 1984; Dal Monte et al., 1987; Grappe et al., 1997, 1998; Padilla et al., 2000; Jeukendrup and Martin, 2001; Defraeye et al., 2010a, 2010b; 2011; Crouch et al., 2014, 2017; Grappe et al., 1997).

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https://doi.org/10.1016/j.jweia.2018.09.015
Received 16 August 2018; Received in revised form 18 September 2018; Accepted 20 September 2018

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Fig. 1. Team time trials with different numbers of riders. Sources: (a) © Arne Mill/frontalvision.com; (b) © Cor Vos; (c) © LottoNL-Jumbo/Cor Vos; (d) © Mauvries/Shutterstock.com. All photos reproduced with permission.

Fig. 2. Cyclist model geometry with definition and values of (1) sagittal torso angle; (2) shoulder angle; (3) elbow angle; (4) forearm angle; (5) hip angle; (6) knee angle; (7) ankle angle.
wind tunnel experiments, were reported by Kyle (1979), McCole et al.
(1990), Hagberg and McCole (1990), Kyle (1991), Broker and Kyle
Broker et al. (1999), Edwards and Byrnes (2007) and Garcia-Lopez et al.
(2008), Broker and Kyle (1995) and Garcia-Lopez et al. (2008) studied
the drag of 5 cyclists in time-trial (TT) position while Martin et al. (1998)
studied 6 cyclists in TT position. The results of previous investigations of
the drag in small in-line groups of drafting cyclists showed reductions
down to 50% of the drag of an isolated rider. More recently, Blocken et al.
(2013) investigated the aerodynamic benefit for a leading cyclist due to
the presence of a trailing cyclist based on CFD simulations and wind
tunnel measurements. It was found that the trailing cyclist can provide a
drag reduction of almost 3% to the leading cyclist due to the upstream
effect exerted by the trailing rider on the
flow. This effect was later confirmed by Defraeye et al. (2014) and Barry et al. (2015) who studied
the aerodynamic drag of four in-line cyclists for a team pursuit, and by
Barry et al. (2016) who analyzed the aerodynamic interactions between
two riders. As a special case of drafting, Blocken and Toplarar (2015)
assessed the aerodynamic benefit for a cyclist by a following car and
Blocken et al. (2016) assessed the aerodynamic benefit for a cyclist fol-
lowed by one, two or three motorcycles. Further drafting studies were
performed by Belloli et al. (2016), Mannion et al. (2018a,b) analyzed a
special case of drafting, i.e. the interaction between the pilot and the
stoker in Paralympic tandem cycling, where both athletes are in much
closer proximity compared to drafting in regular cycling. Another special
case of drafting is riding in a tightly packed peloton. By CFD simulations
and wind tunnel measurements for pelotons of 121 cyclists, Blocken et al.
(2018a) showed that the aerodynamic resistance of a rider well
embedded in the core of the peloton could go down to 5–10% of that of
an isolated cyclist.

The exploitation of the drag reduction by drafting closely behind each
other in view of traveling economy is a well-established principle that is
not only applied in cycling but also in platooning of automotive vehicles
(e.g. Bruneau et al., 2017; Nuszowski et al., 2017) and in the aero-
dynamics of passenger and freight trains (e.g. Lai et al., 2008; Beagles and
Fletcher, 2013; Soper et al., 2014, 2015; Maleki et al., 2017). It is a field
that is expected to gain importance in the coming years in view of the
emergence of autonomous vehicles.

However, in spite of the fact that this principle is well-established, to
the best of our knowledge, systematic studies of the aerodynamic resis-
tance in groups of in-line drafting cyclists of 2 up to 9 riders where the
number of drafting riders and the wheel-to-wheel spacing are varied,
have not yet been published. Therefore, this paper presents such a sys-
tematic analysis for groups of 2 up to 9 drafting cyclists in a single
paceline, with wheel-to-wheel spacings d = 0.05 m, 0.15 m, 0.5 m, 1 m
and 5 m. Computational Fluid Dynamics (CFD) simulations are per-
formed with the 3D RANS equations, the standard k-ε model and scalable
wall functions. The simulations are validated with dedicated wind tunnel
measurements. The target parameters are the drag of every cyclist in the
paceline, the static pressure coefficients around the cyclists and the static
pressure coefficients on the cyclist and bicycle surfaces. Also the average
drag of the whole group and of theoretical larger in-line groups is
analyzed and compared with the average drag of two peloton configu-
rations to provide some insight into traveling economy as a function of
group configuration.

2. Wind tunnel measurements

Fig. 2 shows the full-scale geometry and dimensions of the cyclist
model together with seven angles specifying the cyclist position on the
bicycle. Height and weight of the cyclist were 183 cm and 72 kg,
respectively. The cyclist geometry was obtained by laser scanning. He
was equipped with an aerodynamic helmet and a standard tight-fitting
racing suit with long sleeves. In TT position, the frontal area was
0.34 m². The bicycle was a standard racing bicycle with open wheel at
the front and disk wheel at the rear and a time-trial handlebar. Both
wheels were fixed. The bicycle geometry was simplified, specifically
concerning the front forks, wheel hubs and spokes, pedals, cranks and
handlebars. The chains, sprockets, and also brake and gear cables and
mechanisms were neglected as they were considered small enough not to
influence the characteristic flow around it. The wind tunnel measure-
ments were performed in the aeronautical section of the Wind Tunnel
Laboratory at the University of Liège in Belgium, which has a cross-

Fig. 3. Wind tunnel set-up with models on elevated sharp-edged plate to reduce boundary-layer thickness. Dimensions in mm.

Fig. 4. Quarter-scale models in the wind tunnel.
section of $W \times H = 2 \times 1.5 \text{ m}^2$. A dedicated set-up with an elevated sharp-edge horizontal plate and embedded force balance was developed to limit boundary layer development (Fig. 3). To fully accommodate the models in the wind tunnel at a blockage ratio below 5%, they were manufactured at scale ¼, yielding a blockage ratio below 3.5%. Fig. 4 shows the models in the wind tunnel. Tests were performed at 60 m/s to ensure Reynolds number similarity with the (full-scale) CFD simulations and with reality at 15 m/s cycling speed, which is a typical elite time trial speed. For the wind tunnel tests, three configurations were considered: (i) isolated cyclist; (ii) four drafting cyclists with wheel-to-wheel spacing $d = 0.15 \text{ m}$ (in full scale); (iii) three drafting cyclists with $d = 0.5 \text{ m}$ (full scale). The drag force, i.e. the horizontal component parallel to the wind direction and bicycle, was measured using a force transducer with a conservative maximum error estimate of 1.24% with 95% confidence level, although the actual precision is expected to be much better (Gore, 2016). It should be noted that this error included both systematic and random errors, and that systematic errors were removed by proper zero setting for bias removal prior to every measurement. The data were sampled at 10 Hz for 180 s. During the measurements, air temperature and wind speed were carefully recorded to correct the measurements to the references values of 15 °C and 15 m/s as in the CFD simulations. The measurements were also corrected by subtracting the drag of the base plate (see Figs. 3 and 4) as well as for blockage using the expressions for solid blockage reported by Barlow et al. (1999). The boundary-layer height at the position of the cyclist model was about 6 cm, which is below the feet and pedals of the cyclist. The turbulence of the approach-flow was lower than 0.2%. The measurement results are reported as mean drag forces together with the simulation results in the next sections.

3. CFD simulations – part I: validation

3.1. Computational geometry and domain

For validation, CFD simulations were performed for the three configurations tested in the wind tunnel. The simulations were performed at full scale. Some further simplification were applied to the cyclist model and the models were placed in a computational domain with size according to best practice guidelines (Franke et al., 2007; Tominaga et al., 2008). The sizes of the computational domain were $L \times W \times H = 51.3 \times 17.3 \times 10.3 \text{ m}^3$ for the single cyclist model and $L \times W \times H = 54.7 \times 17.3 \times 10.3 \text{ m}^3$ for both the pacelines with 4 and 3 models. The maximum blockage ratio was 0.2%, which is well below the recommended maximum value of 3% (Franke et al., 2007; Tominaga et al., 2008). Given this low blockage ratio, the CFD simulations were not corrected for blockage.

3.2. Computational grid

The grids were based on grid sensitivity analysis including seven different grids for the isolated cyclist. In two previous studies with the same cyclist geometry (Blocken and Toparlar, 2015; Blocken et al., 2016), a medium-high resolution grid was used in steady RANS simulations with the standard k-ω model and scalable wall functions. In this grid, the wall-adjacent cell center point was at 30 μm from the body surface. The simulations with this grid, turbulence model and near-wall treatment were able to reproduce the wind tunnel drag within 1.2%. In later studies including different cyclist geometries (Blocken et al., 2018a,b; Mannion et al., 2018a,b), it was shown that the simulations for some of these geometries were very sensitive to the computational grid topology and turbulence model. This required very high resolution grids with the wall-adjacent cell center point at only 10 μm from the cyclist and bicycles surfaces and with very fine layers of prismatic grid cells in the boundary layer at the cyclist body and bicycle surfaces, and more advanced turbulence modeling with pseudo-transient simulations based on the SST k-ω or Transition SST k-ω model. These observations suggest that some cyclist geometries are very sensitive to the computational parameters and settings, while others are not.

In the present study, using the cyclist geometry also studied by Blocken and Toparlar (2015) and Blocken et al. (2016), different grid topologies with different grid resolutions were systematically analyzed. In line with the previous studies using this cyclist geometry, steady RANS was employed in combination with the standard k-ω model and scalable wall functions. Seven different grids were made for the isolated cyclist. Grid B was the grid as used in these two previous studies. Grids C1, C2, C3, C4 and C5 were grids in which the distance of the wall-adjacent cell center point from the wall was gradually decreased from 200 μm to 10 μm as indicated in Table 1, but with prismatic grid layers as in the studies by Blocken et al. (2018a,b) and Mannion et al. (2018a,b). Finally, a much coarser grid A was made with near-wall cell sizes exceeding 3 mm and without the prismatic grid layers. The total cell counts per grid are also indicated in Table 1. Fig. 5 compares the computed drag forces on the isolated cyclist on all seven grids. Surprisingly, the grid dependence of the drag force among these seven grids was not large. Although grid convergence seems present when refining the near-wall grid in the grid C series, the results with the medium resolution grid B and the much coarser grid A are not far off. It appears that the accuracy of the drag prediction for this specific cyclist geometry is not very much affected by the choice of steady RANS, the grid resolution within the range considered and the near-wall treatment. This is in line with the findings by Defraeye et al. (2010a,b) who applied LES, RANS and different near-wall treatments for the same cyclist geometry. The reasons for this insensitivity are not totally clear, but are expected to be related to the insensitivity of the position of the separation points on the cyclist body to these computational parameters. Note that for a different cyclist geometry, this sensitivity can be much larger, as shown by Mannion et al. (2018a).

Therefore, the present set of computational parameters can certainly not be considered as generally applicable in studies of cycling aerodynamics. For the present study, we have chosen to retain grid A for further analysis from the viewpoint of sufficient accuracy and also higher grid economy but to subject these results on this grid to an additional validation study for pacelines of 4 and 3 riders. Fig. 6 shows the resulting grid for a paceline of 8 riders with detailed view of the grid around a single rider. The grid for the paceline with 4 riders contained 22,485,356 cells while the grid for the paceline with 3 riders contained 21,932,446 cells.

3.3. Boundary conditions

At the inlet, a uniform velocity of 15 m/s was imposed with a turbulence intensity of 0.2%. These conditions represented the relative air movement due to cycling at this velocity in still air (zero wind speed). The cyclist body surfaces were modeled as a no-slip walls with zero roughness, at which scalable wall functions were assigned (Grotjans and Menter, 1998). For the bottom, side and top boundaries of the domain, a slip-wall boundary was used. At the outlet of the computational domain, zero static gauge pressure was imposed.

3.4. Approximate form of governing equations and solver settings

The 3D steady RANS equations were solved with the standard k-ω model (Jones and Launder, 1972) for closure. The choice of the standard k-ω model was made based on previous extensive validation studies for
the aerodynamics of a single cyclist, including the standard, realizable and Re-normalization Group (RNG) $k$-$\varepsilon$ model, the standard $k$-$\omega$ model, the Shear-Stress Transport (SST) $k$-$\omega$ model and Large Eddy Simulation. This study, conducted for the same cyclist geometry as in this study and reported in (Defraeye et al., 2010b), showed that, for this particular cyclist and bicycle geometry, the standard $k$-$\varepsilon$ model provided the most accurate drag prediction, with an underestimation of 4% compared to the corresponding wind-tunnel result. The choice of the standard $k$-$\varepsilon$ model was also based on the earlier study of the aerodynamic benefit for a cyclist by a following car (Blocken and Toparlar, 2015) and a following motorcycle (Blocken et al., 2016) that used the same cyclist geometry. Pressure-velocity coupling was taken care of by the SIMPLEC algorithm, pressure interpolation was second order and second-order discretization schemes were used for both the convection terms and the viscous terms of the governing equations. Gradients were computed with the Green-Gauss cell-based method (Ansys, 2013). The simulations were performed with the commercial CFD code ANSYS Fluent 15 (Ansys, 2013) which uses the control volume method. Convergence was monitored carefully and the
iterations were terminated when all residuals showed no further reduction with increasing number of iterations. At this stage, the scaled residuals were about $10^{-4}$ for continuity, $10^{-7}$ for momentum, $10^{-5}$ for turbulent kinetic energy and $10^{-5}$ for turbulence dissipation rate.

3.5. Results

The drag on the isolated cyclist as measured in the wind tunnel was 33.43 N. The drag simulated with CFD, on Grid A, was 33.60 N (a
difference of 0.5%). Given this close agreement in spite of the differences between the wind tunnel model geometry (Fig. 4) and the CFD geometry (Fig. 6), it is clear that some errors had compensated each other. Therefore it was important to extend the validation study beyond the geometry of the isolated cyclist. Fig. 7 compares the drag forces by wind tunnel and CFD for the paceline of 4 cyclists with spacing $d = 0.15$ m and for the paceline of 3 cyclists with $d = 0.5$ m. There are clear deviations between the results for the trailing riders in every paceline, which could be attributed to minor misalignments in the wind tunnel but more likely to the difficulty of reproducing the effect of shear layer gradients and vortex shedding from the leading rider (and subsequent riders) further downstream by steady RANS with the standard k-ε model. In spite of these deviations, the decreasing drag trend down the paceline as measured in the wind tunnel is reproduced by CFD, albeit overestimated by CFD. On the other hand, the largest deviations are found for the second riders, while the deviations for the third and fourth rider are substantially smaller. This could be related to the growth of the wake in width and height downstream along the paceline, which is most pronounced for the first two or three riders while the last rider is almost fully engulfed by this growing wake. Based on this overall good agreement
between wind tunnel and CFD results, the same grid topology and the same other computational settings and parameters were retained for the systematic parametric analysis in the next section.

4. CFD simulations – part II: parametric analysis

4.1. Computational geometry

Simulations were performed for 40 different configurations: pacelines of 2 up to 9 riders with 5 spacings each: \( d = 0.05, 0.15, 0.5, 1 \) and 5 m. While \( d = 0.05 \) m is an unrealistically and dangerously short spacing for riders in a perfectly straight paceline, it was included here because it represents a theoretical minimum distance and because this spacing could be actually be obtained by slightly staggered riding positions. The spacing of 0.15 m on the other hand is a realistic distance regularly observed during races, while also larger distances can occur depending on rider fatigue, maneuvering or because of the accordion effect in bends, when the paceline stretches out. All riders, bicycles and rider positions on the bicycle were identical to that of the isolated rider, to allow a clear comparison.

4.2. Computational settings and parameters

The simulations were performed at full scale. The models were placed in computational domains with sizes according to best practice guidelines (Franke et al., 2007; Tominaga et al., 2008). The width and height of all domains were: \( W \times H = 21.2 \times 12.4 \text{ m}^2 \). The length was adjusted based on the length of the pacelines. It varied from 51.3 m for the

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**Fig. 9.** Drag of every rider in pacelines of 2 up to 9 riders, as a percentage of the drag of an isolated rider. Wheel-to-wheel distance \( d = 0.05 \) m. Right column gives average drag percentage for the whole paceline.
paceline of two cyclists with $d = 0.05 \text{ m}$ to $5 \text{ m}$ for the paceline of 9 cyclists with $d = 5 \text{ m}$. The total cell count varied from $17,118,256$ for the paceline of two cyclists with $d = 0.05 \text{ m}$ to $37,868,358$ for the paceline of 9 cyclists with $d = 5 \text{ m}$. The maximum blockage ratio was 0.2%, which is well below the recommended maximum value of 3% (Franke et al., 2007; Tominaga et al., 2008). Given this low blockage ratio, the CFD simulations were not corrected for blockage. The grid topology was identical to that outlined above and shown in Fig. 6. The boundary conditions were the same as for the validation study except for the turbulence intensity, where $T_{I} = 1 \times 10^{-4}\%$ was adopted for the parametric study, representative of riding in still air, as in (Blocken et al., 2016). The solver settings (approximate form of the governing equations, turbulence model, discretization schemes, etc) were identical to those in section 3.

4.3. Results: Drag percentages

Fig. 8 depicts the drag (in percentage of the drag of an isolated cyclist) that is achieved for every cyclist ($C_1 =$ leading cyclist, $C_2 =$ second cyclist, etc) in pacelines of 2 up to 9 cyclists. The values for different paceline numbers are given in different colors. The following observations are made:

1. Fig. 8a–d shows that in all pacelines with $d = 0.05 \text{ m}$ up to $d = 1 \text{ m}$, the leading rider experiences a small but significant drag reduction, in line with the original findings by Blocken et al. (2013). This effect has almost disappeared in Fig. 8e when $d = 5 \text{ m}$. The reason is that every cyclist not only disturbs the flow behind him or her but also in front him or her, although the latter effect is much smaller. This effect, as explained in (Blocken et al., 2013), is present because of the elliptical character of the governing Navier-Stokes equations for subsonic flow. It will be called “subsonic upstream disturbance” in the remainder of this paper.

2. Fig. 8a–d shows another consequence of this “subsonic upstream disturbance”: for pacelines of 6 riders and more, it is not the last rider that experiences the lowest drag. Indeed, this last rider is the only rider in the pacelines that does not benefit from the subsonic

<table>
<thead>
<tr>
<th>$d = 0.15 \text{ m}$</th>
<th>AVG: 100%</th>
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<tr>
<td>100%</td>
<td>AVG: 100%</td>
</tr>
<tr>
<td>98.0%  64.4%</td>
<td>AVG: 81.2%</td>
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<td>97.7%  62.2%  52.2%</td>
<td>AVG: 70.7%</td>
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<td>AVG: 64.1%</td>
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<tr>
<td>97.5%  61.7%  49.8% 44.7% 44.3%</td>
<td>AVG: 59.6%</td>
</tr>
<tr>
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<td>AVG: 56.5%</td>
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<td>AVG: 54.2%</td>
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<td>AVG: 52.4%</td>
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<tr>
<td>97.5%  61.6%  49.6% 44.1% 42.0% 41.1% 40.7% 40.8% 42.0%</td>
<td>AVG: 51.1%</td>
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Fig. 10. Drag of every rider in pacelines of 2 up to 9 riders, as a percentage of the drag of an isolated rider. Wheel-to-wheel distance $d = 0.15 \text{ m}$. Right column gives average drag percentage for the whole paceline.
upstream disturbance by a trailing rider behind him or her. The effect is small but significant and of about the same order as the benefit for the leading rider.

3. Fig. 8a–e all show that drafting yields large benefits: depending on the spacing, the drag of the second rider in a paceline reduces down to about 60–70% of that of an isolated rider, while the drag of the third rider reduces down to about 50–63% that of an isolated rider, and the drag decreases as we move down the paceline. However, as suggested by the above-mentioned observation (2), the minimum drag is not experienced by the last rider, even not for the case of the large spacing $d = 5$ m. Nevertheless, for long pacelines, i.e. 6 riders or more, the 5th rider and all following riders have a very similar drag. The reason is that the extension of the wake in width and height behind the first rider continues up to about rider number 5 to 6, and then this width and height remain constant, as do the pressures exerted on the cyclist bodies present in this wake at these positions. As a result, being positioned further down the paceline or further down this wake does not provide any substantial additional benefit.

4. The relatively small differences in drag reductions obtained at different distances ($d = 0.05$ m, $0.15$ m, $0.5$ m, $1$ m) might suggest that riders can easily leave a larger distance between each other without major aerodynamic losses and still travel economically this way. However, in a competition where sometimes winning or losing is determined by times less than a second, every benefit should be exploited so minimum distances should be attempted. As an example, in the 100th Tour de France in 2013, Team Orica-Green Edge won the TTT with a 0.75 s lead to Omega-Pharma Quick-Step. In the subsequent 2013 TTT World Championship, Omega-Pharma Quick-Step won the TTT with a 0.88 s lead to Team Orica-Green Edge.

To provide more direct quantitative information, Figs. 9–13 show the drag percentage of every rider – compared to an isolated rider – in the different pacelines. The lowest drag percentages for every paceline are marked in green color. In addition, the right column gives the average drag percentage for the whole paceline, which could be considered as a measure of “traveling economy” (at least in terms of aerodynamic resistance) for the whole group. The following observations are made for Fig. 9:

1. For a paceline of 2 identical riders, the benefit for the leading rider is 2.4%, but this benefit increases when more riders are added to the paceline, up to 3.0% for pacelines of 7 riders or more. This indicates that the subsonic upstream disturbance, although limited in magnitude, does stretch out for quite a long distance upstream.

### Table: Drag of every rider in pacelines of 2 up to 9 riders, as a percentage of the drag of an isolated rider. Wheel-to-wheel distance $d = 0.5$ m. Right column gives average drag percentage for the whole paceline.

<table>
<thead>
<tr>
<th>$d = 0.50$ m</th>
<th>100%</th>
<th>AVG: 100%</th>
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<tbody>
<tr>
<td>98.7% 65.2%</td>
<td>82.0%</td>
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<tr>
<td>98.4% 63.4% 53.6%</td>
<td>71.8%</td>
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<td>98.4% 63.4% 52.3% 48.6%</td>
<td>65.7%</td>
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<tr>
<td>98.4% 63.4% 52.0% 47.1% 46.6%</td>
<td>61.5%</td>
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<tr>
<td>98.4% 63.3% 51.9% 46.8% 45.2% 45.7%</td>
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<td>98.4% 63.3% 51.8% 46.7% 44.8% 44.0% 43.6% 44.8%</td>
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<tr>
<td>98.4% 63.3% 51.8% 46.7% 44.8% 44.0% 43.6% 43.6% 44.6%</td>
<td>53.4%</td>
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</table>
2. The benefit at a fixed position (e.g. second or third rider) increases as the paceline includes more riders, which is also due to the upstream subsonic disturbance.

3. The drag decreases as one moves further down the paceline and for pacelines up to 5 riders, it reaches a minimum for the last rider. This is due to the expanding of the wake that originates from the first rider and the fact that this expansion only continues down to position 5. For pacelines with 6, 7, 8 and 9 riders, the position with the lowest drag is not the last one. For the pacelines with 6, 7 and 8 riders, the position with the lowest drag is the one but last position. This is attributed to the combination of two effects: (1) the widening of the wake that stops at about position 5 after which all positions have almost the same benefit from drafting in this wake; (2) the subsonic upstream disturbance, which applies for all riders except the last one, who has nobody drafting in his/her wake. For a paceline of 9 riders, the lowest drag is found at position 7, although the difference with position 8 is very minor.

4. The lowest drag in the paceline is about 40%, and for a paceline of 9 riders, 6 riders experience about this amount of drag.

5. The average drag for the whole paceline decreases rapidly as the number of riders in the line increases, especially for small groups. For a paceline with 9 riders, it decreases down to about 50%. This indicates that in terms of aerodynamic resistance, riding in a paceline of 9 riders is about twice as efficient as riding alone.

The following observations are made for Fig. 10:

1. Compared to \( d = 0.05 \) m, the magnitude of the subsonic upstream disturbance decreases substantially when the spacing increases to \( d = 0.15 \) m. For a paceline of two riders the drag reduction for the leading rider is 2%, and for a paceline of 9 riders it is 2.5%.

2. The benefit at a fixed position (e.g. second or third rider) increases as the paceline includes more riders, which is again due to the upstream subsonic disturbance. However, given the larger spacing, this effect is less pronounced as in Fig. 9.

3. Similar to Fig. 9, the drag decreases as one moves further down the paceline and for pacelines up to 5 riders, it reaches a minimum for the last rider. For pacelines with 6, 7, 8 and 9 riders, the position with the lowest drag is not the last one. For the pacelines with 6, 7 and 8 riders, the position with the lowest drag is the one but last position. For a paceline of 9 riders, the lowest drag is found at position 7, although the difference with position 8 is very minor.

4. The lowest drag in the paceline is only slightly higher than in Fig. 9, i.e. also about 41%, and for a paceline of 9 riders, 6 of them experience about this amount of drag.

5. Similar to Fig. 9, the average drag for the whole paceline decreases rapidly as the number of riders in the line increases, down to about 51% for a paceline with 9 riders. This indicates that in terms of aerodynamic resistance, also for \( d = 0.15 \) m, riding in a paceline of 9 riders is about twice as efficient as riding alone.

The following observations are made for Figs. 11–13 that show the effect of increasing the wheel-to-wheel spacing:

1. As the spacing increases from 0.5 to 5 m, the maximum effect of the subsonic upstream disturbance goes from 1.6% down to 0.1%.

2. Nevertheless, this effect remains responsible for the fact that starting from a certain length of the paceline, it is not the last rider that experiences the lowest drag.
3. For a given spacing (d = 0.5 m, 1 m or 5 m), the drag experienced by the 6 last riders in the paceline of 9 riders is about the same, although when changing the spacing, this value increases from about 45% over about 48% to about 60% for d = 0.5 m, 1 m and 5 m, respectively.

4. Similar to Figs. 9 and 10, the average drag for the whole paceline decreases rapidly as the number of riders in the line increases. For a paceline of 9 riders, the average drag goes down to about 53%, 56% and 66% for d = 0.5 m, 1 m and 5 m, respectively. In spite of the larger spacing d = 5 m, riding in such pacelines of multiple riders still offers large benefits: the average drag is only 71% for a paceline of 5 riders and only 66% for a paceline of 9 riders.

4.4. Results: static pressure coefficients in cross-sectional planes

Some more insights in the aerodynamic interaction in pacelines can be obtained from Figs. 14 and 15 that display contours of the static pressure coefficient in a vertical centerplane and a horizontal plane at 1 m height for all pacelines and for d = 0.15 m and 1 m. The static pressure coefficient \( C_p \) is defined as:

\[
C_p = 2 \frac{P - P_0}{\rho U^2_{\infty}} \tag{1}
\]

where P is the static pressure and \( P_0 \) the reference static pressure (= ambient atmospheric pressure). The following observations are obtained from Fig. 14:

1. Compared to an isolated rider, the underpressure area (blue area) behind the leading rider decreases in size and magnitude when one or more trailing riders is/are added. This is due to the interaction between the overpressure area in front of the trailing rider and the underpressure area behind the leading rider which causes the aerodynamic benefit for the leading rider. For the longer pacelines, e.g. that with 9 riders, the underpressure area and the underpressure in it are slightly larger for the last rider than for the riders at more upstream positions, because of the same interaction between overpressure and underpressure areas.

2. For all pacelines, the overpressure area (red – orange) in front of the trailing rider is evidently the largest one. This area and the overpressure in it decrease as we move down the paceline from the first over the second and third to the fourth rider, after which further reductions become difficult to distinguish.

3. The combination of observations (1) and (2) explains the resulting drag percentages outlined in section 4.3.

The following observations are obtained from Fig. 15:

1. Due to the larger distance, the subsonic upstream disturbance (i.e. the interaction between overpressure and underpressure areas) is difficult to detect in the contours.

2. Similar to Fig. 14, for all pacelines, the overpressure area (red – orange) in front of the trailing rider is the largest one and this area and the overpressure in it decrease as we move down the paceline from the first over the second and third to the fourth rider, after which further reductions become difficult to distinguish.

4.5. Results: static pressure coefficients on cyclist and bicycle surfaces

Figs. 16 and 17 show contours of the static pressure coefficient on the...
cyclist and bicycle surfaces for \( d = 0.15 \) m and \( d = 1 \) m. Note that it is not the total pressure that is shown here, as relative to a reference coordinate system fixed to the road surface, the dynamic pressure at the cyclist and bicycle surfaces is a constant non-zero value as it results from the movement of the paceline at 15 m/s. In these figures, the colorbar has been cut to the interval \([-0.5; 0]\) to highlight some specific features. From Fig. 16, the following observations are obtained:

1. Compared to the leading rider, the underpressure/suction (blue-green-yellow area) on the back of the trailing riders is clearly less pronounced. So the drag reduction for the trailing riders is not only the result of the reduced overpressure on the front part of the cyclist, as outlined in section 4.4, but also the result of the reduced underpressure on the rear part of the cyclist. Note that the pressure coefficients on especially the rear wheel should not be misinterpreted, as they yield a lateral force that has no influence on the drag.

2. Moving down the paceline, the pressure coefficients and their distribution on the cyclists are very similar, except for the last cyclist in the long pacelines, where some small differences can be observed.

From Fig. 17, similar observations are obtained although the extent of the changes down the paceline is less pronounced than in Fig. 16 due to the larger spacing.

5. Discussion

This study is subjected to a number of limitations. In order to allow clear conclusions to be drawn, all cyclists and bicycles had the same geometry and all cyclists had the same position on the bicycle. In reality, every cyclist is different and, evidently, differences will occur in the resulting drag in pacelines compared to that presented in this paper. The cyclists, both in the CFD simulations and in the wind tunnel measurements, had static legs and the wheels were fixed. Earlier research has shown that the aerodynamic drag of a pedaling cyclist, averaged over one pedaling revolution, is quite similar to that of the same cyclist with the crank almost horizontal (Crouch et al., 2016). In spite of these limitations, the results in this paper provide a basic framework and starting point for analyzing aerodynamic drag in real pacelines.

This study only considered cyclists riding in still air so it did not consider crosswinds. Crosswinds will cause pacelines to be formed in staggered positions or echelons. Crosswind studies on pacelines are a...
subject of future research. Crosswind studies for isolated cyclists have been reported by Fintelmann et al. (2014, 2015), Belloli et al. (2016) and Mannion et al. (2018c) and these studies together with the present study can form the basis for crosswind studies for pacelines. Future studies should focus on the optimal echelon formation in TTTs under crosswind conditions, where the optimal positioning of the cyclists will be a function of the yaw angle under study. Evidently, rider morphology will play a role here and future studies should explore the differences in aerodynamically optimal TTT configurations both for riders with identical morphology and riders with different morphologies.

The present study only focused on aerodynamic resistance, while rolling resistance and drive-train and wheel-bearing resistance were not addressed. Nevertheless, this study, to the best of our knowledge, provides the first openly published systematic analysis of drag in single pacelines in which the number of riders in the paceline and the wheel-to-wheel spacing are systematically varied.

The numbers in the right column in Figs. 9–13 indicated the average drag percentage for a rider in a paceline compared to that of a single rider. This showed that for a typical paceline spacing of 0.15 m, riders in a paceline of 9 riders – assuming they alternate properly and take an equal share of the workload – travel at a drag that is about half that of an isolated rider. The question arises as to how efficient theoretical and much longer pacelines would be. To estimate this, we theoretically expand the paceline with $d = 0.15$ m up to 10, 20, 40, 60, 80, 100 and 120 riders. To the additional riders in every paceline, we assign the minimum drag of the 9- rider paceline in Fig. 10, i.e. 40.7% of the drag of an isolated cyclist. This is a reasonable assumption as shown by the asymptotic behavior towards a minimum drag value in Fig. 8b. The results are shown in Fig. 18 by the light blue bars labeled L10 to L120. For single pacelines above 40 riders, the average drag is only slightly above 40% that of an isolated rider. Finally, we compare these values with the average drag obtained for two pelotons of 121 cyclists, as studied in (Blocken et al., 2018a,b). Although the cyclist geometry in that study is somewhat different from that in the present study, this comparison provides a first insight in the difference in traveling economy in terms of aerodynamic resistance. The average drag in the two previously studied pelotons A and B, dense and sparse, is 21.1 and 21.9% of that of an isolated rider from these pelotons, respectively. This demonstrates the very large benefit of not only drafting but especially of riding in closely spaced staggered positions.

In this study, groups up to 9 cyclists have been analyzed. The current (at the time of publishing this paper) number of riders in the major multistage UCI World Tour races has been brought down to 8, and the UCI is considering bringing it further down to 7. However, to ensure the widest applicability of the results of this study, we considered all numbers up to a total of 9.

6. Conclusions

This paper presented a systematic analysis of the drag of single pacelines of 2 up to 9 riders with wheel-to-wheel spacings $d = 0.05, 0.15, 0.5, 1$ and $5$ m. A total of 47 Computational Fluid Dynamics (CFD) simulations were performed with the 3D RANS equations, standard $k$-$\epsilon$ model and scalable wall functions and validated with wind tunnel measurements. The following main conclusions were obtained:

- Two beneficial effects of drafting are governing the drag in pacelines in the absence of crosswind: (1) the well-known drafting effect, by
Fig. 16. Static pressure coefficient contours on the surfaces of riders and bicycles, for 1, 4, 6 and 9 riders in the paceline, for \(d = 0.15\) m.

Fig. 17. Static pressure coefficient contours on the surfaces of riders and bicycles, for 1, 4, 6 and 9 riders in the paceline, for \(d = 1\) m.
which a trailing rider experiences less overpressure on the front part of the body and less underpressure (suction) on the back part of the body due to being present in the slipstream of the leading rider(s); (2) the less well-known subsonic upstream disturbance effect, by which a leading rider experiences less underpressure (suction) on the back part of the body because of the presence of trailing rider(s) in his/her wake.

- There is little difference in the drag numbers for riders in pacelines spaced by $d = 0.05$ m and $d = 0.15$ m. This indicates that riding closer to each other than $d = 0.15$ m, which is dangerous, might not be worthwhile.
- Large differences are only obtained when the spacing becomes very large, i.e. $d = 1$ m and especially $d = 5$ m. Nevertheless, for all

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**Fig. 18.** (a) Comparison of average drag (as percentage of drag of an isolated rider) for pacelines of 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 20, 40, 60, 80, 100 and 120 riders, and for two peloton configurations A and B; (b,c) Configurations of pelotons A and B; (d,e) drag percentages for every rider position in the pelotons A and B.
spacings from $d = 0.05$ m to $d = 5$ m, many of the main tendencies remain present.

- In all pacelines and for all spacings up to $d = 1$ m, the leading rider experiences a small but significant drag reduction due to the subsonic upstream disturbance.

- Drafting yields large benefits for the trailing riders: depending on the spacing, the drag of the second rider in a paceline reduces down to about 60–70% of that of an isolated rider, while the drag of the third rider reduces down to about 50–63% that of an isolated rider, and this reduction increases moving down the paceline.

- For pacelines up to 5 riders, the last rider experiences the lowest drag. But for pacelines of 6 riders and more, it is not the last rider that experiences the lowest drag, due to the subsonic upstream disturbance effect.

- For long pacelines, i.e. 6 riders or more, the 5th rider and all following riders have a very similar drag. The reason is that the extension of the wake in width and height behind the first rider continues downstream up to rider number 5 or 6, and then this width and height remain approximately constant, as do the pressures exerted on the cyclist bodies present in the wake at these positions. As a result, being further down the paceline or further down this wake does not provide a substantial additional benefit.

- For a typical paceline spacing of 0.15 m, riders in a paceline of 9 riders travel at a drag that is about 50% that of an isolated rider.

- For very long – atypical and hence theoretical – pacelines, e.g. 120 riders, the estimated average drag in two previously studied peloton configurations is about 50% of that of the long paceline. This demonstrates the very large benefit of not only drafting but especially of riding in closely spaced staggered positions.

Future research will focus mainly on drafting in crosswind conditions and on circular and double paceline configurations.

Acknowledgements

The authors thank the technical support team of the Department of the Built Environment at Eindhoven University of Technology, Ing. Jan Diepens, Geert-Jan Maas and Stan van Asten for preparing and setting up the wind tunnel experiments in the wind tunnel laboratory in Liège. The authors also acknowledge the partnership with ANSYS CFD. This work was also sponsored by NWO Exacte en Natuurwetenschappen (Physical Sciences) for the use of supercomputer facilities, with financial support from the Nederlandse Organisatie voor Wetenschappelijk Onderzoek (Netherlands Organization for Scientific Research, NWO).

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