

CFD simulations of the flow around a cyclist subjected to crosswinds

Fintelman, Danielle; Hemida, Hassan; Sterling, Mark; Li, Francois-Xavier

DOI:

[10.1016/j.jweia.2015.05.009](https://doi.org/10.1016/j.jweia.2015.05.009)

License:

Creative Commons: Attribution-NonCommercial-NoDerivs (CC BY-NC-ND)

Document Version

Peer reviewed version

Citation for published version (Harvard):

Fintelman, D, Hemida, H, Sterling, M & Li, F-X 2015, 'CFD simulations of the flow around a cyclist subjected to crosswinds', *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 144, pp. 31-41.
<https://doi.org/10.1016/j.jweia.2015.05.009>

[Link to publication on Research at Birmingham portal](#)

Publisher Rights Statement:

After an embargo period this article is subject to the terms of a Creative Commons Attribution Non-Commercial No Derivatives license.

Checked September 2015

General rights

Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

- Users may freely distribute the URL that is used to identify this publication.
- Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
- User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
- Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

Take down policy

While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.

CFD simulations of the flow around a cyclist subjected to crosswinds

Fintelman, D.M.*¹⁾, Hemida, H.²⁾, Sterling, M.²⁾, Li, F.-X.¹⁾

1) School of Sport, Exercise and Rehabilitation Sciences, University of Birmingham, UK

2) School of Civil Engineering, University of Birmingham, UK

** Corresponding author. E-mail address: dmf144@bham.ac.uk. (D.M. Fintelman)*

Word count: 6656

ABSTRACT

For the first time, an extensive numerical study of the effect of crosswinds on the flow around a cyclist on a bicycle with stationary wheels has been undertaken for crosswind (yaw) angles ranging from 0° - 90° . The flow field and the aerodynamic forces have been obtained using three numerical techniques: Reynolds Averaged Navier Stokes (RANS), Detached Eddy Simulation (DES) and Large Eddy Simulation (LES). RANS models have been undertaken for all the range of yaw angles to provide a general insight of the flow around a cyclist, whilst DES and LES have been undertaken at 15° yaw angle in order to investigate the time-varying flow physics in detail. The aerodynamic forces have been compared with a series of wind tunnel experiments. The RANS results showed the development of large flow separation around the bicycle with increasing yaw angles. The instantaneous flow structures and the auto spectral densities of the time histories of the force coefficients are identified and revealed that the DES and LES turbulence models are able to predict the dominant frequencies found in the physical experiments. This work provides an improved understanding of the flow characteristics around a cyclist in crosswinds that will hopefully help to improve the safety of cyclists.

27 KEYWORDS

28 Crosswinds, cyclist, aerodynamics, turbulence model

29

30 HIGHLIGHTS

- 31 • The flow around a cyclist on a bicycle at different crosswinds is investigated
- 32 • The CFD results are compared with experimental data
- 33 • Different turbulence models are compared
- 34 • Flow structures around a cyclist in crosswinds are explored

35

36 1 INTRODUCTION

37 Crosswinds can have an impact on the performance, stability and safety of cyclists, e.g., ~5% of
38 all single bicycle accidents are caused by crosswinds (Schepers and Wolt, 2012). Despite several
39 fatalities, relatively little work has been undertaken investigating the effect of crosswinds with
40 most numerical research focusing on minimising the overall aerodynamic drag (Defraeye et al.,
41 2010a; Griffith et al., 2012; Hanna, 2002; Lukes et al., 2004). Two numerical cycling crosswind
42 studies investigated the aerodynamics of isolated spoked bicycle wheels (Godo et al., 2009;
43 Karabelas and Markatos, 2012). These studies enabled both the aerodynamic loads and flow
44 structures around isolated bicycle wheels to be quantified. Both studies have demonstrated that the
45 side forces acting on a spoked wheel are up to about 5-6 times higher than the drag forces, hence
46 having an impact on the stability of the cyclist. However, a study by Barry et al. (2012), showed
47 that the wheels and cyclist cannot be considered separately, due chiefly the flow interaction
48 between them. In a numerical study reported by Hanna (2002), the full cyclist and bicycle system
49 has been analysed. In the study a comparison has been made between disk and spoked rear wheels
50 at different crosswind flow velocities (0-13 m/s). The side wind was positioned at a yaw angle of
51 90° to the cycling direction (the yaw angle is defined as the angle between the effective side wind,
52 U_{eff} , and the direction of travel of the cyclist, U_x , as shown in Fig. 1). The study showed that a disk

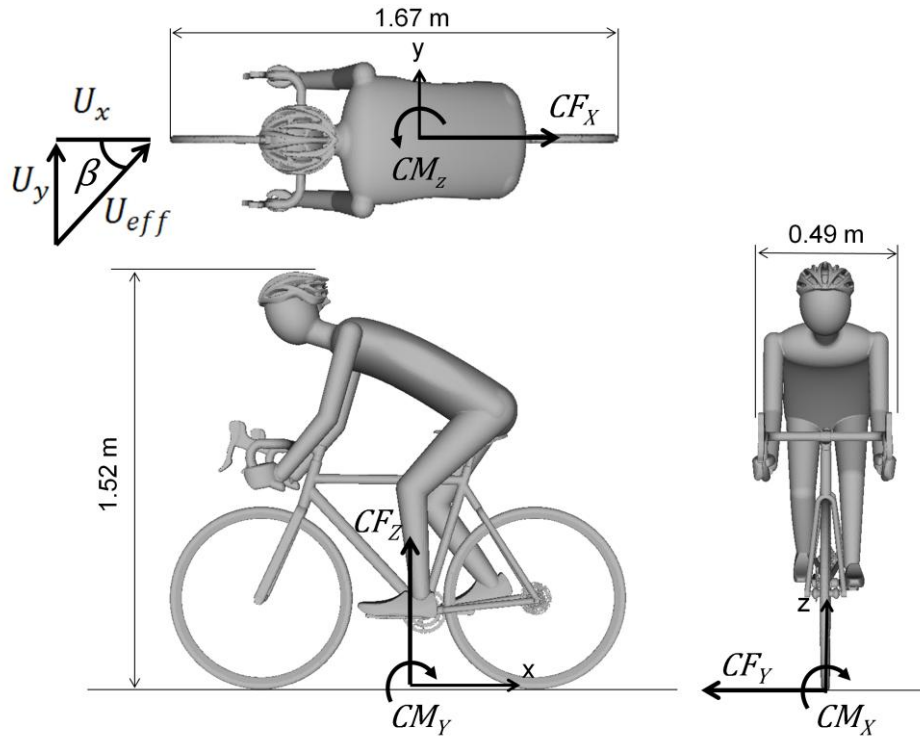
53 wheel reduced the drag by approximately 2% compared to spoked wheels, but in a crosswind of
54 ~9 m/s the side forces were doubled. As the research has been conducted for the British Cycling
55 team, details of the simulations and the results are limited and without validation precaution has to
56 be taken about the validity of the results.

57 Barry et al. (2012) undertook a series of wind tunnel experiments to investigate the effect of
58 crosswind on the bicycle system for yaw angles up to 30° and discovered that when positioned in
59 a time trial position, the side forces increase linearly with increasing yaw angles between 5-30°. It
60 is found that the side forces are approximately double the drag forces at 15° yaw angle. It was also
61 demonstrated that the wheel type, including spoked and disk wheels, has a significant effect on the
62 aerodynamic drag and yaw moments. Although the work of Barry et al. study (2012) outlines the
63 importance of examining crosswind at yaw angles often experienced by cyclists, it does not give
64 real insight into the overall flow field. For many types of ground vehicles, the critical wind angle
65 has been shown to be around 30°, such as busses (François et al., 2009; Hemida and Krajnović,
66 2009b), passenger cars (Ryan and Dominy, 1998) and trains (Diedrichs, 2010; Hemida and
67 Krajnović, 2009a). For cyclists however, experimental results showed that there is no specific
68 critical yaw angle (Fintelman et al. 2014). It is likely that even at small crosswind yaw angles
69 (~15°), the stability and performance of the cyclist will be influenced by crosswinds. It is however
70 reasonable to assume that with increasing yaw angles, it becomes more difficult for cyclists to
71 control the bicycle. Several bicycle accidents are reported as a result of strong crosswinds ("Bike
72 Rider Blown Over By Heavy Wind," 2011; "Bobridge blown off his bike," 2012; "Cyclist's death
73 was an accident," 2001). The effect of crosswinds with yaw angles up to 90° has been investigated
74 experimentally by Fintelman et al. (2014). The results showed that the actual aerodynamic loads
75 arising from crosswinds can be up to about 2.5 times the aerodynamic drag with spoked wheels
76 and cyclist in dropped position. In addition, it has been observed that the torso angle of the cyclist
77 has little effect on the side force coefficient. In contrast, the bicycle significantly affects the
78 aerodynamic forces; at large yaw angles, the bicycle is responsible for approximately 60% of the
79 total side force coefficient. However, this study does not provide information about the flow

80 characteristics around the cyclist that causes the aerodynamic forces and moments. Noting this,
81 the research discussed below was undertaken in order to provide detailed information on the
82 overall aerodynamic forces and moments and to provide an insight into the surrounding flow field,
83 thus laying the foundations for future improvements in cycling stability and performance.

84 In order to obtain accurate flow field and surface pressure of the bicycle and the cyclist, numerical
85 simulations based on Reynolds Averaged Navier Stokes equations (RANS) using both $k-\epsilon$ and
86 SST $k-\omega$ models have been undertaken. Yaw angles considered range between $0-90^\circ$. The surface
87 pressure and the surface shear stresses are integrated to obtain the aerodynamic forces and
88 moments on both the bicycle and cyclist with the results compared to previous physical
89 simulations (Fintelman et al., 2014). In addition, Detached Eddy Simulations (DES) and Large
90 Eddy Simulations (LES) are undertaken on a bicycle and a cyclist in order to gain an insight in the
91 instantaneous flow physics around the cyclist at 15° yaw angle, since this is found to be a common
92 crosswind yaw angle (Guzik et al., 2013) in cycling.

93 Section 2 of this paper briefly outlines the wind tunnel experiments that were undertaken in order
94 to compare the numerical simulations, whilst section 3 outlines details relating to the
95 computational models. Section 4 addresses the numerical details of the simulations, whilst section
96 5 outlines the numerical accuracy. This is followed by the results and discussion in section 6 and
97 finally in section 7 the main conclusions are drawn.



98

99 *Fig. 1: Geometry and dimensions of cyclist and directions of the aerodynamic force and moment*
 100 *coefficients.*

101

102 **2 WINDTUNNEL EXPERIMENTS**

103 Details relating to the physical simulations can be found in Fintelman et al. (2014) and are briefly
 104 reiterated for the benefit of the reader. The wind-induced forces on a bicycle with mannequin are
 105 measured in the open wind-tunnel facility at the University of Birmingham UK. The wind-tunnel
 106 has a cross-sectional area of $2 \times 2 \text{ m}^2$ and length of 10 m. A constant crosswind flow velocity, U_{eff} ,
 107 of 9.91 m/s is maintained in the wind tunnel with a corresponding average turbulence intensity of
 108 0.67 %. The mannequin is placed in a dropped position on a road bicycle with stationary wheels
 109 as shown in Fig. 2a and is connected to a six-component force balance (Kistler type 9281B,
 110 Kistler Instruments, Winterthur, Switzerland) which is used to measure the aerodynamic forces
 111 and moments. The aerodynamic forces were repeatable to within $\pm 0.05 \text{ N}$ and the uncertainty was
 112 approximately 2%.



113

114 *Fig. 2: (a) Full-scale bicycle and mannequin used in wind tunnel experiments and (b) geometry of the*
 115 *bicycle and cyclist in simulations.*

116

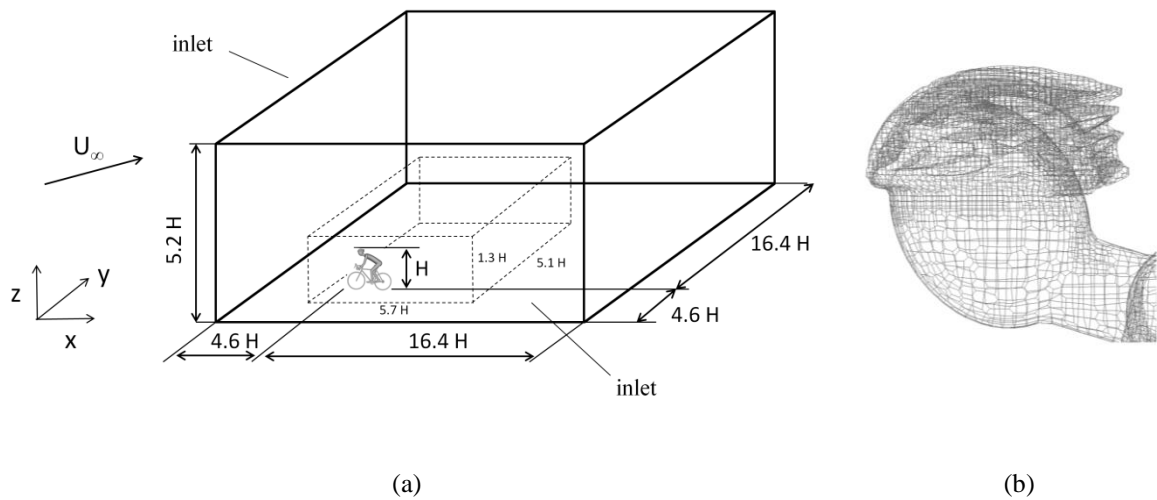
117 3 COMPUTATIONAL MODELS

118 To simulate realistic flow conditions, a high level of complexity and detail are maintained in the
 119 CAD model of the bicycle and mannequin (Fig. 2b). However, modelling of small objects such as
 120 the spokes and cables have been omitted to simplify the geometry. A generalized computational
 121 domain is used as shown in Fig. 3a, in which H (1.52m) represents the height of the cyclist from
 122 the ground. The dimensions of the computational domain are large enough that blockage area
 123 effects can be neglected (maximal blockage area of 0.3%). Similar to the wind tunnel setup, a
 124 uniform effective velocity, U_{eff} , of 9.91 m/s is applied for all different yaw angles, β . This gives
 125 a Reynolds number of 1.0×10^6 , based on the effective wind velocity and the height of the cyclist
 126 from the ground. The velocity in the main inlet direction, U_x , and in the crosswind inlet direction,
 127 U_y , is calculated as:

$$128 \quad U_x = U_{eff} \cos(\beta), U_y = U_{eff} \sin(\beta). \quad (1)$$

129 No-slip boundary conditions are used on the surface of the model and on the ground to accurately
 130 match the wind tunnel experiments. A free-slip velocity boundary condition is applied on the
 131 upper boundary of the computational domain. In all simulations the wheels are considered static,

132 as the effect of the rotation on the wheels without spokes is found to be small; k- ϵ RANS
 133 simulations were undertaken without crosswinds and with crosswinds of 90° , in which the rims
 134 and tires rotated at 29.494 rad/s (equivalent to a tangential velocity of 9.91 m/s). The results (not
 135 reported here) showed that the aerodynamic coefficients in the main wind direction decreased by
 136 less than 1.8 % when implementing rotating rims and tires, which is within the limits of the
 137 uncertainties of the physical experiments. It is worth noting that rotation of the spokes can have an
 138 impact on the side force magnitude (Karebelas and Markatos 2012). However for ease of
 139 simplicity, spoke and leg movement was not included in the simulations.
 140



141 *Fig. 3: (a) Computational domain, (b) surface mesh of the helmet of the cyclist for the RANS simulations.*

142
 143 RANS simulations were used to predict the average flow velocity, pressure and aerodynamic
 144 responses. Two different steady RANS simulations were performed with different turbulence
 145 models: the standard k- ϵ and the SST k- ω models. Wall functions are applied close to the wall
 146 based on the log-law. These turbulence models are commonly applied in numerical sport
 147 simulations, for example in swimming (Silva et al., 2008; Zaïdi et al., 2008), rowing (Zhang et al.,
 148 2009), ski jumping (Meile et al., 2006) and bobsleigh (Dabnichki and Avital, 2006). They have

149 also been shown to give a reasonable performance when applied in cycling (Defraeye et al.,
150 2010b; Griffith et al., 2014).

151 In addition to the simulations using RANS models, the more computationally expensive but
152 accurate standard detached eddy simulation (DES) are undertaken for the flow at 15° yaw angle.
153 This is to provide information about the instantaneous and time-averaged flow at this particular
154 yaw angle. The hybrid DES approach combines the RANS close to the walls and Large-eddy
155 simulation (LES) in the region outside the boundary layers. This model replaces the turbulent
156 length scale function l_{RANS} with a modified length scale function, l_{DES} :

$$157 \quad l_{DES} = \min (l_{RANS}, C_{DES}\Delta) \quad (2)$$

158 where C_{DES} is a constant (0.65) and Δ is the largest dimension of the grid cell in all three
159 directions, i.e., $\Delta = \max (\delta x, \delta y, \delta z)$. The length scales increases with the distance from the wall.
160 Therefore, close to the wall the model behaves like the RANS model and the length scale is:

$$161 \quad l_{DES} = l_{RANS} \ll C_{DES}\Delta . \quad (3)$$

162 In the far field the length scale is given by:

$$163 \quad l_{DES} = C_{DES}\Delta \ll l_{RANS} \quad (4)$$

164 The most commonly used Spalart-Allmaras one-equation turbulent model is applied (Spalart and
165 Allmaras, 1994). DES has been successfully used for the aerodynamics of a ground vehicle (Flynn
166 et al., 2014; Hemida and Krajnović, 2009b).

167 Finally, the Large Eddy Simulations (LES) are used to make an accurate comparison of the
168 simulation results of the different turbulence model approaches at a common crosswind yaw angle
169 of 15°. LES is the most computational expensive turbulent model used in this research, but is
170 considered to be the most accurate of all mentioned models, particularly when large scale flow
171 unsteadiness is significant (which is likely to be the case for cyclists and bicycles). With the
172 increase in computational power, LES has been used extensively in the study of the flow around
173 small scale models of trains and cars subjected to cross winds (Hemida and Baker, 2010; Hemida

174 and Krajnovic, 2010; Tsubokura et al., 2010). In the LES approach, the large eddies containing the
 175 most energy are resolved, whilst a sub-grid scale model is used for the eddies smaller than the grid
 176 size. The velocity is decomposed into a filtered part and sub-grid scale component. The filtered
 177 Navier-Stokes equations are derived for the large scale eddies. The filtered continuity and
 178 momentum equations for an incompressible flow are:

$$179 \quad \frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + 2 \frac{\partial}{\partial x_j} (v + v_t) (\bar{S}_{ij} - \partial \tau_{ij}^r), \quad (5)$$

$$180 \quad \text{and} \quad \frac{\partial \bar{u}_i}{\partial x_i} = 0,$$

181 where \bar{u}_i and \bar{p} are the filtered velocity and pressure, v_t the turbulent viscosity, \bar{S}_{ij} the resolved
 182 strain rate tensor and τ_{ij}^r the subrid scale stresses. The Smagorinsky sub-grid model is used to
 183 derive the sub-grid scale Reynolds stresses by calculating the turbulence viscosity:

$$184 \quad v_t = (C_S f_d \Delta)^2 \sqrt{2 \bar{S}_{ij} \bar{S}_{ij}}, \quad (6)$$

185 where C_S the Smagorinsky constant (0.1) and f_d is the van Driest damping function.

186

187 4 NUMERICAL DETAILS

188 The open-source CFD package ‘‘OpenFOAM’’ is used to perform all the simulations with the three
 189 dimensional finite volume to solve the flow. The SIMPLE algorithm is implemented in the
 190 simulations to couple the pressure and velocity. In the RANS simulations, the gradients are
 191 computed with a least square second order scheme. The pressure interpolation is performed with
 192 the second order central differencing scheme. The convection and viscous terms are solved with
 193 the second order upwind scheme. In the DES and LES simulations, the time discretization has
 194 been approximated by the second order implicit backward scheme. Gradients are computed with
 195 the second order central differencing scheme. A central difference-upwind stabilised transport
 196 scheme is used for the convection terms. This scheme blends 25% second order upwind with 75%

197 central difference interpolation to stabilise the solution whilst maintaining second order behaviour.
198 The induced numerical dissipation plays an important role in stabilizing the convergence. In the
199 transient simulations, a constant time step of $\Delta t = 0.00001$ sec has been used. This time step
200 ensures that the maximum Courant-Friederichs-Lewy (CFL) number is lower than 1.0. The time
201 history of the aerodynamic coefficients has been obtained for each time step. Convergence is
202 monitored and simulations stopped when the residuals were stable and the maximum normalized
203 residual of each turbulent equation has been converged to at least 10^{-4} . The total wall time of the
204 fine mesh of the RANS, DES and LES approach running at 16 processors was about 17 hours, 905
205 hours and 1357 hours respectively.

206

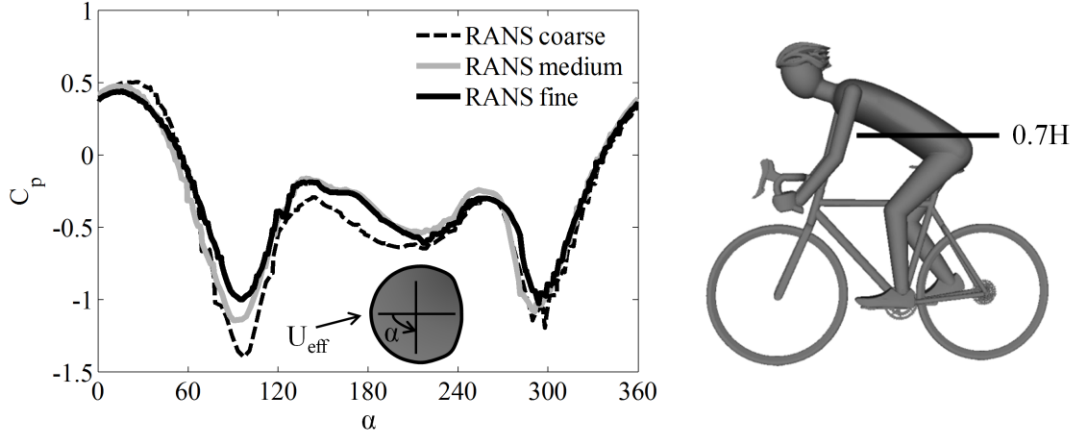
207 5 NUMERICAL ACCURACY

208 To investigate the effect of the grid size on the RANS results, three different meshes (coarse,
209 medium and fine) are evaluated with different number of nodes: 3.5×10^6 , 8.7×10^6 and 17.9×10^6 ,
210 respectively. The averaged normal wall distance y^+ of the cyclist for the different RANS meshes
211 are 82, 60 and 43 respectively. Fig. 3b shows an example of the surface mesh of the cyclist's
212 helmet. Fig. 4 shows the surface pressure of the cyclist at a height of $0.7 H$, obtained from the
213 RANS coarse, medium and fine meshes. The pressure distribution is expressed in terms of the
214 local pressure coefficient, C_p , which is defined as:

$$215 \quad C_p = \frac{p - p_\infty}{0.5 \rho U_{eff}^2}, \quad (7)$$

216 where p is the local pressure, p_∞ the free stream pressure and ρ the air density. A good agreement
217 (Root Mean Square error = 0.09) is found between the RANS fine and medium mesh.

218



219

220 *Fig. 4: Pressure distribution around the surface of the main body of the cyclist obtained from the coarse,*
 221 *medium and fine mesh of the RANS $k-\varepsilon$ simulations at $\beta=15^\circ$.*

222

223 In addition to the pressure distribution, the aerodynamic forces (expressed in coefficient form)
 224 were compared. The drag force coefficient CF_X , side force coefficient CF_Y , lift force coefficient
 225 and CF_Z are defined as:

$$226 \quad CF_X = \frac{F_X}{0.5A\rho U_{eff}^2}, CF_Y = \frac{F_Y}{0.5A\rho U_{eff}^2}, CF_Z = \frac{F_Z}{0.5A\rho U_{eff}^2}, \quad (8)$$

227 where A is the total frontal area of the cyclist and bicycle at 0° yaw angle (0.55 m^2), U_{eff} is the
 228 effective flow velocity (m/s), and F_X , F_Y , and F_Z are the drag force, side force and lift force,
 229 respectively. The coordinate system adopted and thus the directions of these forces are shown in
 230 Fig. 1. The aerodynamic force coefficient for the different grid sizes of the RANS models are
 231 shown in Table 1. The results of the RANS medium simulation compare well to those of the fine
 232 simulation. The grid convergence index (GCI) is used to quantify the error of the fine grid (Celik
 233 et al., 2008) and is defined as:

$$GCI_{fine} = \frac{F_S |\varepsilon|}{r^p - 1}$$

234 where F_S is the safety factor, ε the relative error between the fine and medium mesh, r the grid
 235 refinement factor and p the order of accuracy. The safety factor is set to 1.25. The numerical
 236 uncertainty in the fine grid solution for the drag coefficient CF_X and the side force coefficient CF_Y

237 are 0.4 % and 0.2 % respectively. These levels of agreement between the results obtained from the
238 RANS fine and medium meshes suggest that the resolution of the fine mesh is adequate to
239 correctly predict the flow and hence no further mesh refinement is needed. From this point all the
240 RANS results are from the fine mesh unless otherwise explicitly stated.

241 In the RANS simulations, standard wall functions are used to solve the near wall region, requiring
242 a less refined mesh close to wall. In the LES simulations, the accuracy of the results is dependent
243 on the grid size. In particular in the near wall region a fine mesh is required. Therefore, an
244 additional refinement box of dimensions 3.2 m x 0.8 m x 1.66 m (L x W x H) is added into the
245 LES mesh. In addition, a higher surface based refinement level is applied. The total number of
246 nodes in the LES mesh is 26.7×10^6 , consisting of 84% of hexahedra elements, 15% polyhedral
247 elements and 1% of prisms, tetrahedral wedges and tetrahedral elements. To be able to make an
248 objective comparison between the LES and the DES simulation results, an identical mesh is used
249 in both simulations. This allows a direct comparison of these two turbulence approaches, the grid
250 influence being eliminated. This implies that the transition from LES to RANS in the DES will
251 take place closer to the wall and consequently the DES will acts more like a LES model in most of
252 the computational domain. A mesh sensitivity analysis has been carried out on the DES and LES
253 simulation by performing a simulation on an even finer mesh, consisting of 41.7×10^6 nodes. The
254 normal wall distances of the cyclist for the coarse and fine mesh are about 5.2 and 3.4
255 respectively. The results illustrate a reasonable agreement with the results of the coarser DES and
256 LES mesh as shown in Table 1 (CF_x error difference of about 1.0% and 0.3% respectively).

257

258

259

260

261

262 *Table 1: Force coefficients refinement of the RANS $k-\varepsilon$ model and the DES simulations*

	CF_X	CF_Y	CF_Z
RANS Coarse	0.653	0.148	0.116
RANS Medium	0.586	0.227	0.081
RANS Fine	0.596	0.231	0.099
DES Coarse	0.508	0.243	0.182
DES Fine	0.513	0.250	0.180
LES Coarse	0.612	0.211	0.184
LES Fine	0.610	0.232	0.160

263

264

265 6 RESULTS AND DISCUSSION

266 *6.1 Aerodynamic force coefficients*

267 Fig. 5a shows the variation of the aerodynamic drag forces, side forces, lift forces and rolling
 268 moments of the bicycle and cyclist for different yaw angles, obtained from the RANS simulations
 269 and the experiments. The rolling moment coefficient CM_X is defined as:

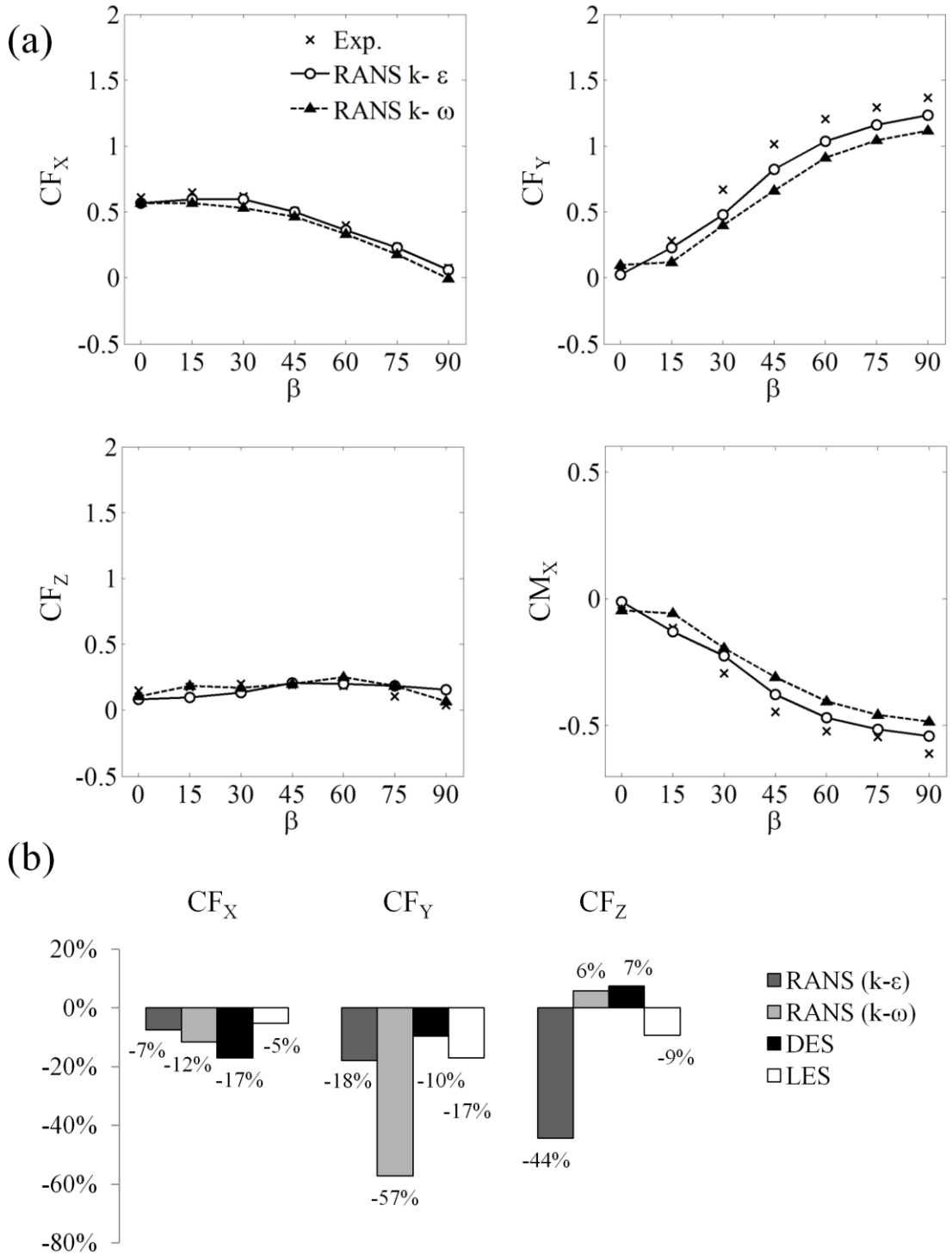
$$270 \quad CM_X = \frac{M_X}{0.5AH\rho U_{eff}^2}, \quad (9)$$

271 where M_X is the rolling moment. The direction of application of the rolling moment is shown in
 272 Fig. 1. The rolling moment tends to rotate the bicycle about its longitudinal axis. For stability and
 273 safety, the side force and rolling moment coefficients are most important. The results show that
 274 the aerodynamic side force and the drag coefficients are a function of yaw angle and for the case
 275 of CF_Y , significant variations can be observed. Large side forces, yaw moments and roll moments
 276 are likely to have a strong impact on the bicycle stability. The RANS simulations illustrate similar
 277 trends to the experimental data with small variations in the drag force ($\sim 9\%$) and lift force ($\sim 7\%$)
 278 across the entire range of the examined yaw angles (Fig. 5a). Larger variations are observed for

279 the side forces (~21%) and the rolling moment (~11%). Of the two RANS model approaches, the
280 k- ϵ model demonstrates the best performance, showing a better prediction of the drag and side
281 force coefficients. The better performance of the k- ϵ model is likely caused by the over prediction
282 of the turbulent kinetic energy and hence the turbulent viscosity, which has an impact on the
283 aerodynamic forces (Makowski and Kim, 2000). The overall under prediction of the aerodynamic
284 forces of the k- ϵ and SST k- ω models are likely to be a consequence of the failure of the RANS
285 models to correctly represent the flow physics in areas of considerable separation and
286 reattachment regions. Furthermore, it is possible that for large yaw angles ($> 60^\circ$), ~52% of the
287 under prediction of the side forces may be due the treatment of the modelling of the wheels
288 (Karabelas and Markatos, 2012). However, it should be noted that this explanation should be
289 interpreted with care since Karabelas and Markatos (2012) did not consider the interaction
290 between bicycle and cyclist and this is felt to have a larger influence on the aerodynamics forces.

291 The results of the DES and LES are in a reasonable agreement with the experimental data as
292 shown in Table 2 and Fig. 5b. It should be noted that at 15° yaw angle the actual magnitude of the
293 side forces are small, which ensures that even small differences between the actual and predicted
294 results in a relatively large percentage error. With increasing yaw angles, the percentage
295 differences will reduce. All the CFD techniques under predict the drag and side force coefficients
296 at the crosswind yaw angle of 15° . The under prediction could be assigned to a range of different
297 small factors, which together add up to quantifiable differences. First of all there are small
298 geometrical differences and simplification of the geometry, such as the exclusion cables and
299 spokes. The contribution of the spokes to the total side forces at different yaw angles is
300 numerically investigated by Karabelas and Markatos (2012). They found that for an isolated
301 stationary wheel at a yaw angle of 15° , the spokes increase the side forces by about 0.5N. The
302 spokes could therefore explain approximately 60% of the under prediction of the side forces.

303 Secondly, it should be appreciated that in the physical modelling, there was slight buffeting of the
304 mannequin in the y-direction largely due to the mannequin induced turbulence, which given the
305 nature of the experiments meant that the geometry of the mannequin-cycle altered slightly during



306

307 *Fig. 5: Comparisons of the aerodynamic force coefficients obtained in the experiments and*
 308 *different turbulence models expressed as: (a) absolute value at different yaw angles, (b)*
 309 *percentage error for the drag at 15° crosswind yaw angle.*

310

311

312 the tests compared to the numerical simulations. Finally, the variations could be associated with
313 the inaccuracy of the turbulence models to capture all scales and to correctly predict the flow
314 separation and attachments. The best performance is seen for the LES simulations, having a drag
315 coefficient error of approximately 5% compared with the experimental data (Fig. 5b). The DES
316 approach shows a reasonable good agreement for the lift and side forces (variation <10%),
317 however larger discrepancies of about 17% are found for the drag force, which is the dominating
318 force direction at the 15° crosswind yaw angle. The less accurate performance of the DES
319 compared with the LES is a result of the capturing of less eddies and the not resolving of the
320 eddies scaled with the grid cells in the boundary layer.

321 The relative contributions of the mannequin and bicycle to the aerodynamic coefficients are
322 shown in Table 2. Comparable results are found for the simulations and the experiments. About
323 70% of the total drag force coefficients CF_x and rolling moment coefficients CM_x are caused by
324 the mannequin in both the experimental work and simulations. The contribution is smaller for the
325 side force coefficients CF_y , where the mannequin contributed to about ~34-49%. In the
326 simulations, the bicycle has a lower contribution to the CF_y , which is likely caused by the
327 simplification of the geometry (i.e. no spokes, cables, chain etc). Finally, for both the experiments
328 and the simulations, the main contribution of the lift force coefficients is the mannequin (around
329 90-110%).

330 In the CFD results, a distinction is made between the pressure forces and the skin friction forces.
331 The skin friction is caused by the viscous stress in the boundary layer around the bicycle and
332 cyclist. In all the numerical investigations undertaken in this report, approximately 3% of the total
333 drag forces and approximately 2% of the total side forces can be attributed to skin friction
334 respectively. These relatively low viscous forces are comparable with similar investigations
335 concerning an isolated cyclist (Defraeye et al., 2010b). As the mannequin-bicycle model used in
336 the CFD calculations is smoother than that in the physical experiments, it is expected that the
337 predicted viscous forces in the experiments are slightly higher than the computed ones. However,
338 due to the nature of the physical experiments this hypothesis cannot be verified.

339 *Table 2: Aerodynamic coefficients for the DES and LES simulations together with the*
340 *experimental results at $\beta=15^\circ$. The total aerodynamic coefficients and the relative contribution of*
341 *the bicycle and mannequin are given. The percentage of the relative contribution of the*
342 *mannequin and bicycle to the total aerodynamic coefficients are presented.*

		Total (Mannequin and Bicycle)	Mannequin	Bicycle
CF_x	DES	0.513	0.359 (70%)	0.154 (30%)
	LES	0.610	0.440 (72%)	0.171 (28%)
	Experiments	0.644	0.449 (70%)	0.195 (30%)
CF_y	DES	0.250	0.123 (49%)	0.128 (51%)
	LES	0.232	0.107 (46%)	0.125 (54%)
	Experiments	0.281	0.095 (34%)	0.186 (66%)
CF_z	DES	0.180	0.197 (109%)	-0.015 (-8%)
	LES	0.160	0.171(107%)	-0.011 (-7%)
	Experiments	0.178	0.155 (87%)	0.023 (13%)
CM_x	DES	-0.107	-0.070 (65%)	-0.037 (35%)
	LES	-0.104	-0.069 (66%)	-0.035 (34%)
	Experiments	-0.114	-0.083 (73%)	-0.031 (27%)

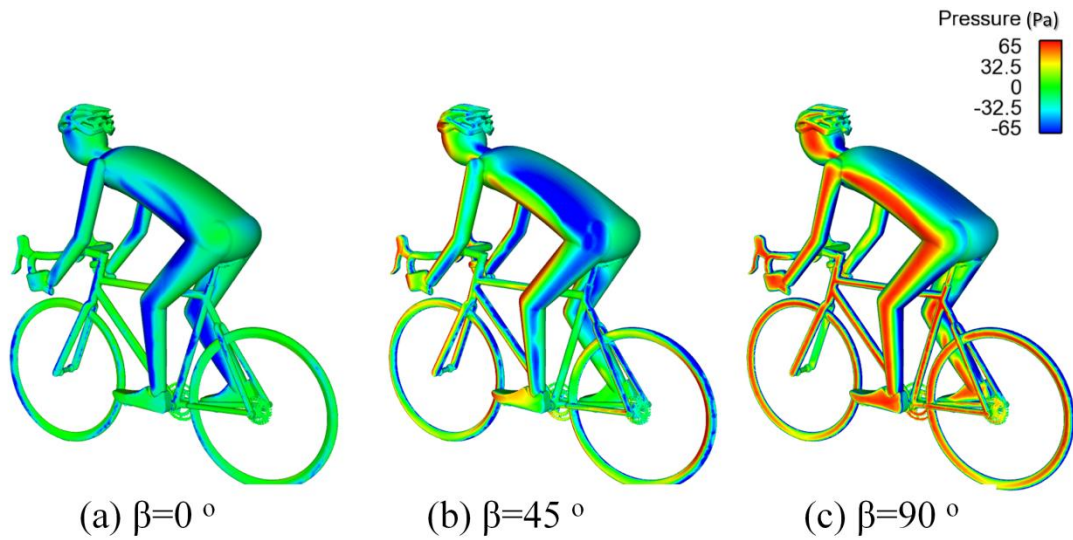
343

344

345 *6.2 Time-averaged flow*

346 Fig. 6 shows the surface pressure distribution, obtained from the k- ϵ simulation at different yaw
347 angles. At $\beta = 0^\circ$, low pressure regions appear at the sides of the body where the vortex shedding
348 takes place. By increasing the yaw angle, an area of suction pressure develops at the back of the
349 cyclist and high pressure regions develop on the upper lower limbs and the abdomen. At 90° yaw
350 angle, high pressure areas develop at the windward side of the cyclist, whilst the back and leeward
351 sides of the cyclist are dominated by low pressure regions. At this yaw angle, the suction pressure

352 is balanced by a developed suction pressure on the front side of the cyclist (not shown in the
353 Figure) and this explains the low drag coefficient at large yaw angles ($> 60^\circ$).

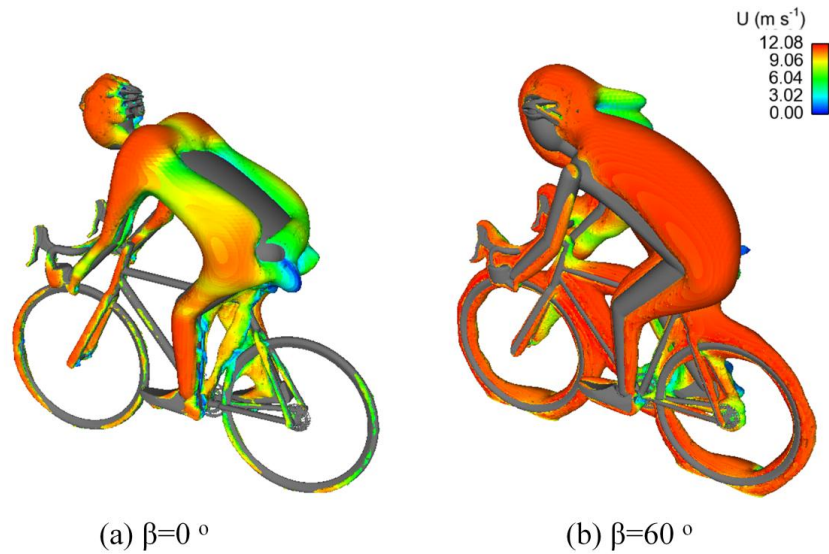


354

355 *Fig. 6: Pressure distribution on the cyclist at different crosswind yaw angles obtained from the*
356 *RANS $k-\epsilon$ simulations.*

357

358 The isosurface of the pressure around the cyclist at $C_p = -0.240$ for yaw angles of 0° and 60° is
359 shown in Fig. 7. For the case of no crosswind (0° yaw angle), the pressure is approximately
360 symmetrical with the concentration of low pressure around the sides of the cyclist. However, at a
361 yaw angle of 60° , the low pressure surface is located behind and at the leeward side of the cyclist
362 and bicycle. In particular at large yaw angles, the bicycle starts to contribute to the turbulent flow
363 around the cyclist which leads to an increase in the side force and rolling moment. This
364 phenomenon has been also observed in the physical experiments, where for 60° yaw angle the
365 bicycle was found to account for approximately 60% of the total side force coefficient; whilst at
366 0° yaw angle the bicycle accounts for only about 20% of the total drag (Fintelman et al., 2014).



367

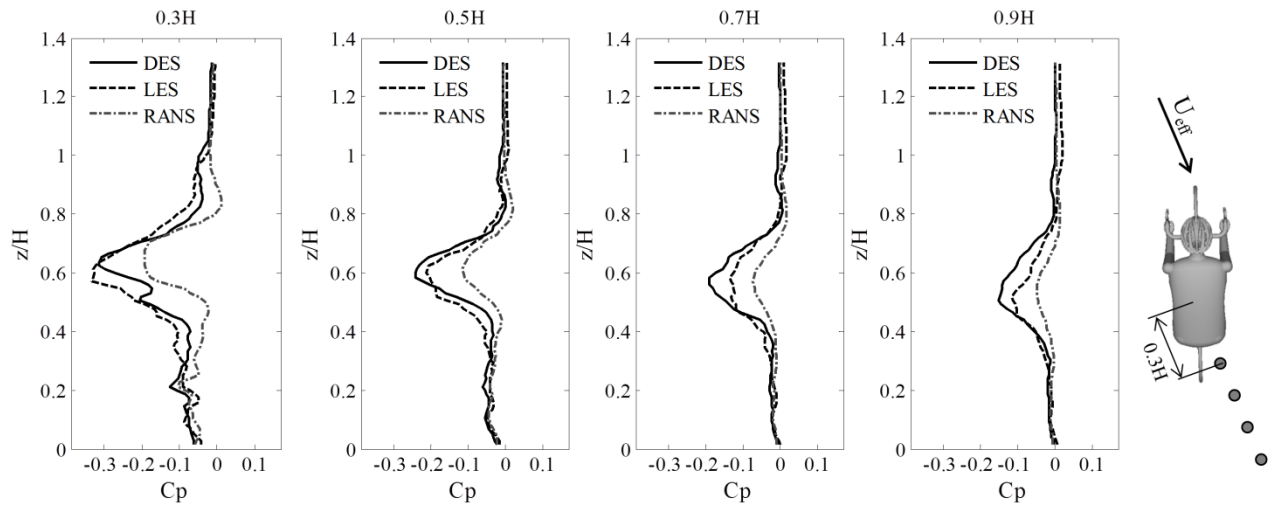
(a) $\beta=0^\circ$

(b) $\beta=60^\circ$

368 *Fig. 7: Isosurface of the pressure at $C_p = -0.240$ at different yaw angles, coloured with the*
 369 *instantaneous velocity and obtained from the RANS $k-\epsilon$ simulations; (a) $\beta=0^\circ$; (b) $\beta=60^\circ$.*

370

371 The time-averaged pressure at different locations in the direction of the main flow at a crosswind
 372 yaw angle of $\beta=15^\circ$ is shown in Fig. 8. The positions considered are at a distance of 0.3H, 0.5H,
 373 0.7H and 0.9H from the cyclist. The negative peak pressure in the wake decreases with increasing
 374 distance from the cyclist. All turbulence models considered are approximately consistent with one
 375 another in terms of identifying the location of the peak pressure. The largest coefficient of
 376 pressure can be found at a height of about 0.6H, caused by flow structures that are separated from
 377 the back of the cyclist. The deviations with respect to the LES simulation are largest for the RANS
 378 $k-\epsilon$ simulation. Smaller deviations are observed between the more accurate LES and DES results.



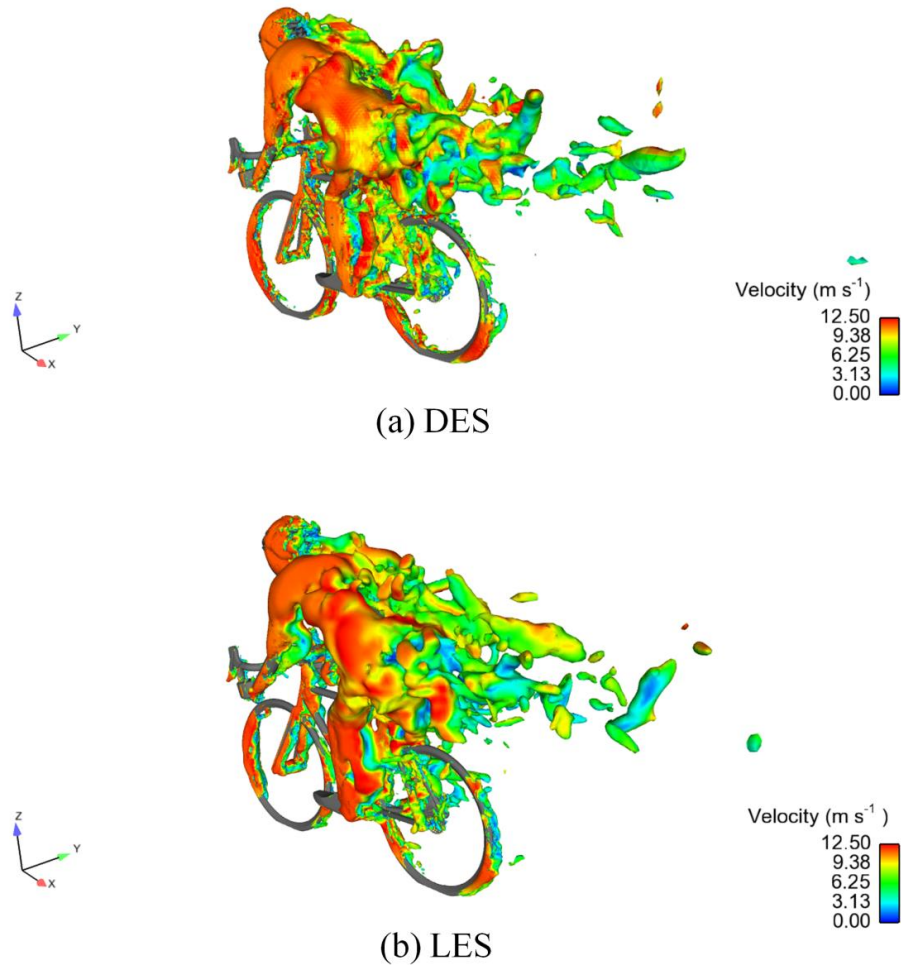
379

380 *Fig. 8: Time-averaged vertical pressure lines at different locations in the wake of the cyclist at*
 381 *yaw angle $\beta=15^\circ$ at a distance of $0.3H$, $0.5H$, $0.7H$, $0.9H$ from the cyclist in the main flow*
 382 *direction.*

383

384 6.3 Instantaneous flow

385 Although RANS simulations are computationally efficient due to their nature, obtaining
 386 instantaneous flow information by such methods is not possible. Therefore DES and LES are used
 387 to determine the instantaneous flow features. Fig. 9 shows the isosurface of the instantaneous
 388 pressure around the cyclist at $C_p = -0.240$ and a crosswind angle of 15° of the DES and LES
 389 simulations. As the centres of the flow vortices are normally associated with low pressure, these
 390 isosurface of constant pressure can be used to infer the flow structures around the bicycle and
 391 cyclist. The results of the DES (Fig. 9a) and LES (Fig. 9b) at random instantaneous time points
 392 look qualitatively similar. In both approaches the instantaneous flow structures show large
 393 vortices shed at the back and leeward side of the body into the wake flow. The flow separates at
 394 the back side of the helmet and the back of the cyclist to form large unsteady structures.
 395 Once these structures completely separate from the surface they tend to form vortex tubes with
 396 axis parallel to the flow direction as shown in Fig. 9.



397

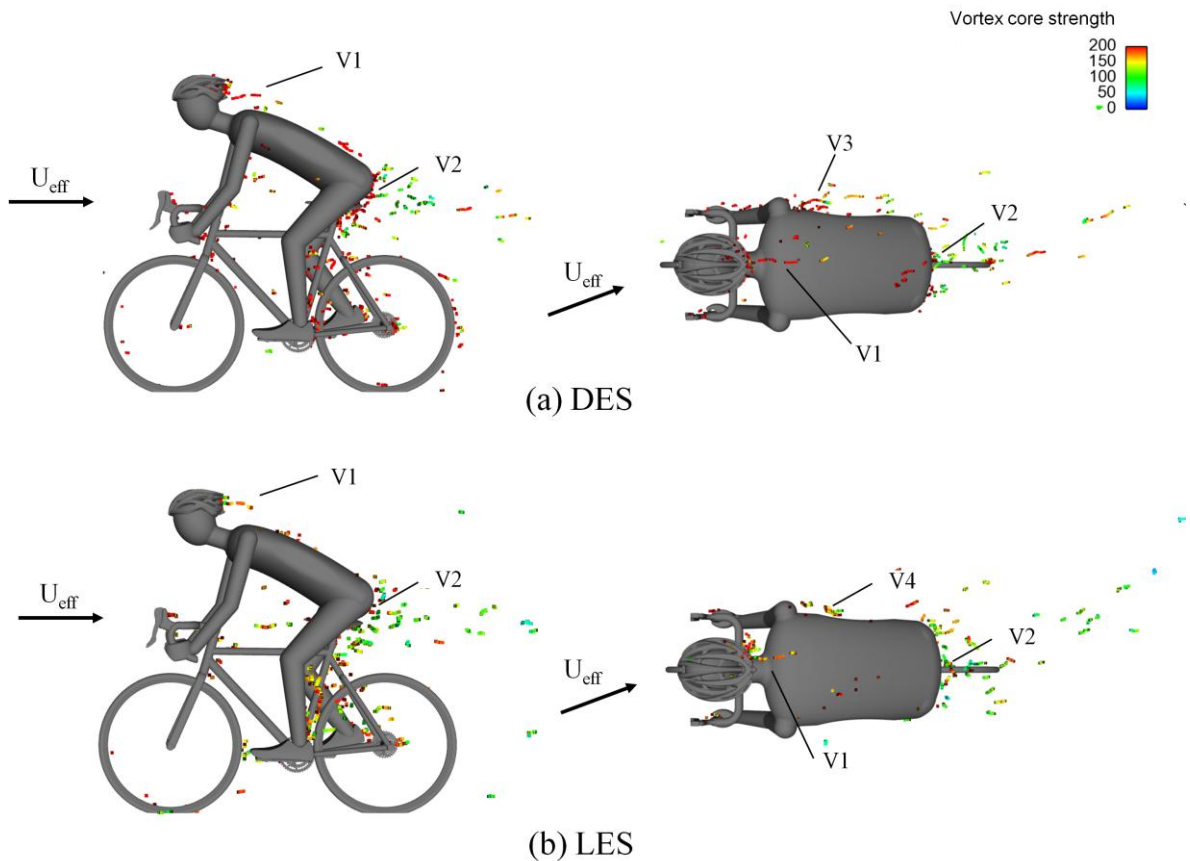
398 *Fig. 9: Instantaneous flow structures around the cyclist subjected to crosswind with a yaw angle*
 399 *of 15° at $C_p = -0.240$ and coloured with the instantaneous velocity, obtained from the (a) DES*
 400 *approach and (b) LES approach.*

401 The vortex cores of the flow around the cyclists are found by means of Eigen analysis. This
 402 method is based on an algorithm of Sujudi and Haimes (1995) and uses the Eigen value of the
 403 velocity gradient tensor to identify the vortex cores. The vortex cores help to give an insight into
 404 the possible distribution of the vortices around the cyclist. The locations of the instantaneous
 405 vortex cores in the flow around the bicycle at 15° yaw angle for the LES and DES turbulence
 406 models are shown in Fig. 10. These vortices are predominantly developing and stretching along
 407 the direction of the main flow and showing the largest strength closest to the body. This underpins
 408 the observation based on the pressure isosurface shown in Fig. 9. Similar main flow vortices are

409 obtained by LES and DES as shown in Fig. 10 in terms of the instantaneous vortex cores. These
410 main vortices are rather small and can be described as follows:

- 411 - Vortex V1 appears due to separation of the flow around the helmet.
- 412 - Vortex V2 originates from a focus very close to the cyclists' gluteus maximus.
- 413 - Vortex V3 and V4 appear at the leeward side of the upper body and originate very close
414 to the back side of the upper arm.

415 The LES resolves more of the small vortex structures than the DES approach and thus many
416 small-scale structures are found predominantly around the lower back of the cyclist compared to
417 the DES simulations.

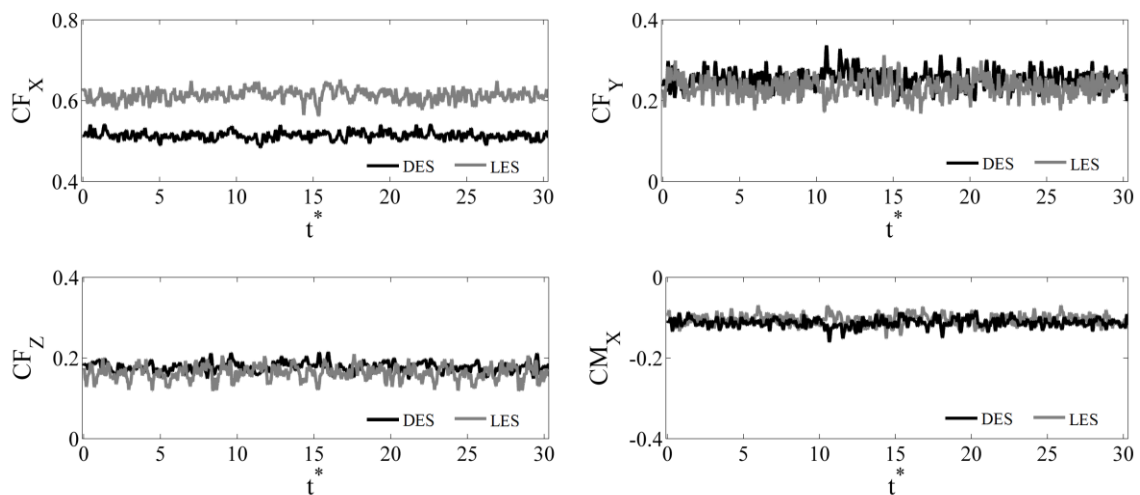


418 *Fig. 10: Location of the instantaneous vortex cores in the flow around a cyclist shown from the*
419 *side view and top view, obtained from the (a) DES simulation and (b) LES simulation. The vortex*
420 *cores are coloured by the vortex core strength.*
421

422 The aerodynamic coefficient time histories are used to reveal the effect of the turbulence on the
 423 forces and moments. It is assumed that the flow is statistically stationary. The time, t , is expressed
 424 in a form of dimensionless time, t^* , as:

$$425 \quad t^* = \frac{tU_{eff}}{H}. \quad (10)$$

426 The time histories of the drag force, side force, lift force and rolling moment coefficients obtained
 427 by the DES and LES simulations are shown in Fig. 11. The shading of vortices at the back and
 428 leeward side of the body into the wake flow shown in Fig. 9, contributes to relatively large
 429 observed variation in the time history of the aerodynamic force coefficients CF_X and CF_Y shown in
 430 Fig. 11. The largest variations in force coefficients are observed in the CF_Y , which is
 431 predominantly caused by the large vortices shed from the mannequin. As shown in Table 3, the
 432 standard deviations of the time histories of both turbulence model approaches are in the same
 433 order of magnitude. The standard deviations of the aerodynamic coefficients of the experiments
 434 are on average about 3 times larger than those of the simulations. These variations are likely not to
 435 be a result of the uncertainties of the force balance, but arise from vibrations and natural
 436 frequencies of the mannequin and bicycle system, causing stronger vortex shedding around the
 437 cyclist as shown in Fig. 9.



438
 439 *Fig. 11: Time history of the aerodynamic coefficients obtained from the fine mesh DES and LES*
 440 *simulations.*

441 *Table 3: Mean and standard deviation of the aerodynamic force responses of the DES*
442 *simulations, LES simulations and windtunnel experiments at 15° crosswind yaw angle.*

	Mean DES	Mean LES	Mean Exp	Std DES	Std LES	Std Exp
CF _X	0.513	0.610	0.644	0.010	0.014	0.046
CF _Y	0.250	0.232	0.281	0.022	0.023	0.075
CF _Z	0.180	0.160	0.178	0.012	0.017	0.042
CM _X	-0.107	-0.104	-0.114	0.011	0.013	0.016
CM _Y	0.292	0.355	0.383	0.006	0.009	0.014
CM _Z	-0.017	-0.018	-0.008	0.004	0.004	0.010

443
444

445 A Fourier transform resulting in the power spectra of the time-varying force coefficients is used to
446 resolve the dominating frequencies. The aerodynamic force frequencies provide an insight into the
447 turbulent frequencies (f) in the flow and represent the crosswind induced force frequencies. The
448 frequencies are expressed in Strouhal number:

$$449 \quad St = \frac{fH}{U_{eff}} \quad (11)$$

450 The power spectra are normalized by the root means square of the turbulent frequencies. All high
451 amplitude peaks in the auto spectral densities of the simulations (Fig. 12a and 12b) can be found
452 in the range $St = 0 - 7$. For the DES simulations, the dominant peak in the drag force coefficient is
453 found at $St = 0.49$, which corresponds to 3.2 Hz. The dominant peak in the LES simulations is
454 at $St = 0.99$, corresponding to 6.5Hz. In the side force coefficients, multiple high amplitude peaks
455 can be found. These peaks are caused by the large range of length scales due to variety of surfaces
456 and angles of the cyclist and bicycle seen by the free stream flow. One of the main frequency
457 components in the side force coefficient is at $St = 2.83$ (E5), corresponding with 18.5 Hz. This
458 frequency coincides with the frequency of the integral length scale of the drag coefficient. The
459 integral length scale describes the size of the large energy containing eddies in the flow. In the
460 side force coefficient frequency spectrum these large eddies originate from the mannequin.

461 Another dominant side force frequency is found at around $St = 1.64$ (E4), which corresponds to
462 10.7 Hz. The lift force of the DES simulations has a characteristic frequency at $St = 0.20$,
463 corresponding to 1.3 Hz. The dominant frequency of the LES simulation is at $St = 0.99$. This peak
464 in the lift force coefficients spectrum is identical to the dominant peak found in the drag forces of
465 the LES simulations.

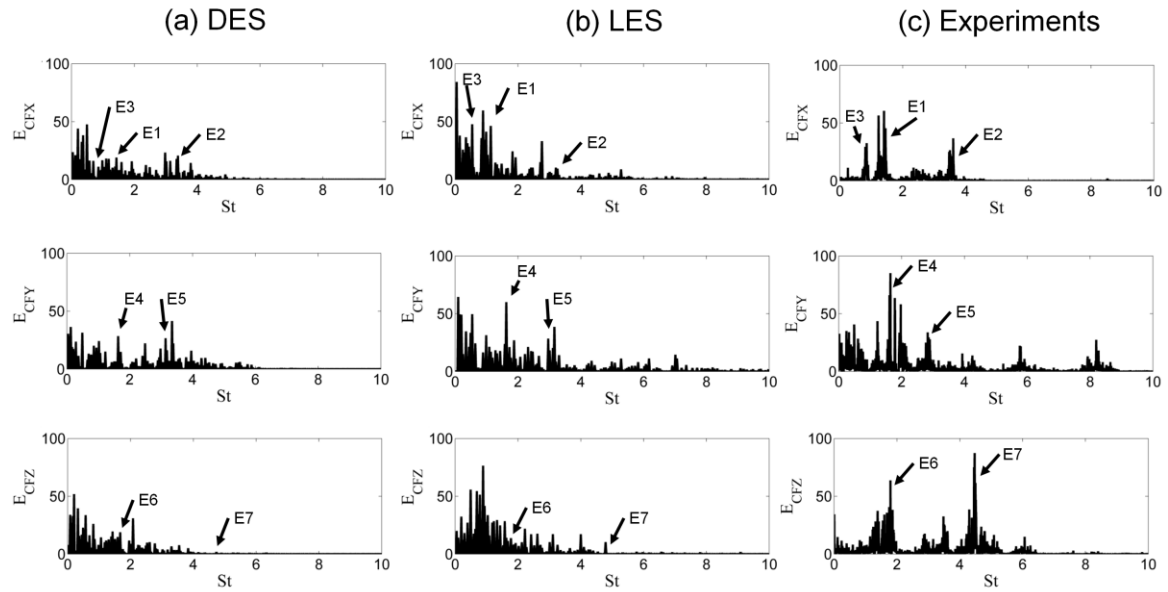
466

467 The auto spectral densities of the simulations are compared with experimental data. Any structural
468 contributions of the bicycle and mannequin have been filtered from the spectra. The experimental
469 force coefficient time histories are shown in Fig. 12c and are dominated by low frequency
470 contents ranging between $St = 0$ and $St = 9$. The values of the dominant frequencies in the
471 experimental work (E1-E7) can be found in Table 4. All dominant frequencies in the auto spectral
472 density of the experiments are also found in the frequency spectra of the DES and LES
473 simulations, albeit not of the same magnitude. This indicates that both approaches are able to
474 predict the important instantaneous flow features. In the drag force coefficient spectrum, which is
475 the major wind direction, similar dominant frequencies (E1-E3) are found in the power spectrum
476 of the LES. However, the highest absolute spectral power is observed in the side force coefficient
477 direction. The dominant peaks E4 and E5 in the side force direction are similar to the dominant
478 peaks of the LES and DES simulations. The normalized spectral power at these frequencies in the
479 LES approach is higher than that of the DES simulations. This suggests that the LES simulations
480 are better capable of predicting the reattachment and separation in the side force direction. Finally,
481 the dominant lift force coefficient frequencies, E6 and E7, are found in the simulations. The
482 relative large discrepancy of the behaviour of the lift force coefficient spectra between the
483 experiments and the numerical results can be explained by the small magnitude of this force and
484 the associated uncertainties which arise when normalising.

485

486

487



488

489 *Fig. 12: Auto spectral density of the aerodynamic coefficients obtained from the fine mesh of the*
 490 *(a) DES simulation, (b) LES simulation, (c) experiments.*

491 *Table 4: Dominant frequencies of the auto spectrum of the force coefficients of the experimental*
 492 *data*

	E1	E2	E3	E4	E5	E6	E7
St	1.40	3.61	0.85	1.64	2.83	1.80	4.47
f (Hz)	9.2	23.6	5.6	10.7	18.5	11.7	29.1

493

494 7 CONCLUSIONS

495 This is the first CFD study investigating the effect of crosswinds on a bicycle and cyclist for a
 496 range of yaw angles from 0 to 90°. RANS analysis has been performed for all yaw angles whilst
 497 DES and LES have been restricted to 15° yaw angle. A reasonably good agreement has been
 498 found between the CFD results and the experimental data across a wide range of yaw angles
 499 (average drag coefficient error of approximately 10%). The results showed that crosswinds have a
 500 significant effect on the aerodynamic force coefficients. All numerical simulations undertaken
 501 have been shown to under-predict the drag and side forces at 15° yaw angle. The LES simulations

502 showed the best performance of all the approaches investigated (drag coefficient error of
503 approximately 5%). At small yaw angles, the upper body of the cyclist predominately affects the
504 aerodynamic forces, whilst at large yaw angles the bicycle has been shown to have an increasing
505 contribution. For the specific case of a 15° yaw angle, complex vortex structures have been
506 identified in the flow and were found mainly in the direction of the free stream flow. These
507 vortices predominantly appear in the flow due to the separation of the flow around the gluteus
508 maximus, helmet, bicycle and upper body. Large vortex structures in the wake of the cyclist are
509 predominantly found at a height of 0.6H. The main frequencies in the time histories of the force
510 coefficients are identified and compared with experimental data. It has been observed that both
511 the LES and DES simulations predict all dominant frequencies found in the experimental work. It
512 could be concluded that despite some dissimilarities between the DES and the LES results, the
513 DES simulations is able to predict the main flow characteristics. This study shows that crosswinds
514 significantly influence the cyclists' aerodynamic forces and the corresponding flow structures.
515 The results therefore have significant influence with respect to the stability and safety of cyclists.

516

517 ACKNOWLEDGEMENT

518 All simulations have been carried out on the Birmingham Environment for Academic Research
519 (BEAR) computational facility. This work has been funded by the University of Birmingham.

520

521

522

523

524

525

526

527

528 REFERENCES

- 529 Barry, N., Burton, D., Crouch, T., et al. (2012). Effect of crosswinds and wheel selection on the
530 aerodynamic behavior of a cyclist. *Procedia Engineering*, 34(0), 20-25. doi:
531 10.1016/j.proeng.2012.04.005
- 532 Bike Rider Blown Over By Heavy Wind. (2011, Jun 17). *7 News The Denver Channel*. Retrieved
533 from <http://www.thedenverchannel.com/news/bike-rider-blown-over-by-heavy-wind>
- 534 Bobridge blown off his bike. (2012, 11 Jan 2012). *ABC News*. Retrieved from
535 <http://www.abc.net.au/news/2012-01-11/bobridge-blown-off-his-bike/3767346>
- 536 Celik, I. B., Ghia, U., Roache, P. J., et al. (2008). Procedure for estimation and reporting of
537 uncertainty due to discretization in CFD applications. *Journal of Fluids Engineering-
538 Transactions of the Asme*, 130(7). doi: 10.1115/1.2960953
- 539 Cyclist's death was an accident. (2001, Nov 02). *The Guardian*. Retrieved from
540 <http://www.retfordtoday.co.uk/news/local/cyclist-s-death-was-an-accident-1-847051>
- 541 Dabnichki, P., and Avital, E. (2006). Influence of the position of crew members on aerodynamics
542 performance of two-man bobsleigh. *Journal of Biomechanics*, 39(15), 2733-2742. doi:
543 10.1016/j.jbiomech.2005.10.011
- 544 Defraeye, T., Blocken, B., Koninckx, E., et al. (2010a). Aerodynamic study of different cyclist
545 positions: CFD analysis and full-scale wind-tunnel tests. *Journal of Biomechanics*, 43(7),
546 1262-1268. doi: 10.1016/j.jbiomech.2010.01.025
- 547 Defraeye, T., Blocken, B., Koninckx, E., et al. (2010b). Computational fluid dynamics analysis of
548 cyclist aerodynamics: Performance of different turbulence-modelling and boundary-layer
549 modelling approaches. *Journal of Biomechanics*, 43(12), 2281-2287. doi:
550 10.1016/j.jbiomech.2010.04.038
- 551 Diedrichs, B. (2010). Aerodynamic crosswind stability of a regional train model. *Proceedings of
552 the Institution of Mechanical Engineers Part F-Journal of Rail and Rapid Transit*,
553 224(F6), 580-591. doi: Doi 10.1243/09544097jrrt346
- 554 Fintelman, D. M., Sterling, M., Hemida, H., et al. (2014). The effect of crosswind on cyclists: an
555 experimental study. *Procedia Engineering*, 72, 720-725. doi:
556 10.1016/j.proeng.2014.06.122
- 557 Flynn, D., Hemida, H., Soper, D., et al. (2014). Detached-eddy simulation of the slipstream of an
558 operational freight train. *Journal of Wind Engineering and Industrial Aerodynamics*,
559 132(0), 1-12. doi: 10.1016/j.jweia.2014.06.016
- 560 François, D., Delnero, J., Colman, J., et al. (2009). *Experimental determination of Stationary
561 Aerodynamics loads on a double deck Bus*. Paper presented at the 11th Americas
562 Conference on Wind Engineering, San Juan, Puerto Rico.
- 563 Godo, M. N., Corson, D., and Legensky, S. M. (2009, 5 - 8 January). An Aerodynamic Study of
564 Bicycle Wheel Performance using CFD. *47th AIAA Aerospace Sciences Meeting
565 Including The New Horizons Forum and Aerospace Exposition*.
- 566 Griffith, M., Crouch, T., Thompson, M., et al. (2012). *Elite Cycling Aerodynamics: Wind Tunnel
567 Experiments and CFD*. Paper presented at the 18th Australasian Fluid Mechanics
568 Conference, Launceston, Australia.
- 569 Griffith, M., Crouch, T., Thompson, M., et al. (2014). Computational Fluid Dynamics Study of
570 the Effect of Leg Position on Cyclist Aerodynamic Drag. *Journal of Fluids Engineering*.
- 571 Guzik, D., Harder, P., Suzuki, M., et al. (2013). 2014 Speed concept: Trek Bicycle Corporation.

- 572 Hanna, R. K. (2002). Can CFD make a performance difference in sport? In S. Ujihashi and S. J.
573 Haake (Eds.), *The engineering of sport 4* (pp. 17-30). Oxford: Blackwell Science Ltd.
- 574 Hemida, H., and Baker, C. (2010). Large-eddy simulation of the flow around a freight wagon
575 subjected to a crosswind. *Computers & Fluids*, 39(10), 1944-1956. doi:
576 10.1016/j.compfluid.2010.06.026
- 577 Hemida, H., and Krajnovic, S. (2010). LES study of the influence of the nose shape and yaw
578 angles on flow structures around trains. *Journal of Wind Engineering and Industrial
579 Aerodynamics*, 98(1), 34-46. doi: 10.1016/j.jweia.2009.08.012
- 580 Hemida, H., and Krajnović, S. (2009a). Exploring Flow Structures Around a Simplified ICE2
581 Train Subjected to A 30° Side Wind Using LES. *Engineering Applications of
582 Computational Fluid Mechanics*, 3(1), 28-41. doi: 10.1080/19942060.2009.11015252
- 583 Hemida, H., and Krajnović, S. (2009b). Transient Simulation of the Aerodynamic Response of a
584 Double-Deck Bus in Gusty Winds. *Journal of Fluids Engineering-Transactions of the
585 Asme*, 131(3). doi: 10.1115/1.3054288
- 586 Karabelas, S. J., and Markatos, N. C. (2012). Aerodynamics of Fixed and Rotating Spoked
587 Cycling Wheels. *Journal of Fluids Engineering-Transactions of the Asme*, 134(1). doi:
588 10.1115/1.4005691
- 589 Lukes, R. A., Chin, S. B., Hart, J. H., et al. (2004). The aerodynamics of mountain bicycles: the
590 role of computational fluid dynamics. In M. Hubbard, R. D. Mehta and J. M. Pallis (Eds.),
591 *The engineering of sport 5* (pp. 104-110).
- 592 Makowski, F. T., and Kim, S.-E. (2000). Advances in External-Aero Simulation of Ground
593 Vehicles Using the Steady RANS Equations. *SAE Technical Paper, 2000-01-0484*. doi:
594 10.4271/2000-01-0484
- 595 Meile, W., Reisenberger, E., Mayer, M., et al. (2006). Aerodynamics of ski jumping: experiments
596 and CFD simulations. *Experiments in Fluids*, 41(6), 949-964. doi: 10.1007/s00348-006-
597 0213-y
- 598 Ryan, A., and Dominy, R. G. (1998). The Aerodynamic Forces Induced on a Passenger Vehicle in
599 Response to a Transient Cross-Wind Gust at a Relative Incidence of 30°. *SAE Technical
600 Paper, 980392*. doi: 10.4271/980392
- 601 Schepers, P., and Wolt, K. (2012). Single-bicycle crash types and characteristics. *Cycling
602 Research International*, 2, 119-135.
- 603 Silva, A. J., Rouboa, A., Moreira, A., et al. (2008). Analysis of drafting effects in swimming using
604 computational fluid dynamics. *Journal of sports sciences and Medicine*, 7, 60-66.
- 605 Spalart, P. R., and Allmaras, S. R. (1994). A One-Equation Turbulence Model for Aerodynamic
606 Flows. *Recherche Aerospatiale*(1), 5-21.
- 607 Sujudi, D., and Haimes, R. (1995). Identification of swirling flow in 3-D vector fields *12th
608 Computational Fluid Dynamics Conference: American Institute of Aeronautics and
609 Astronautics*.
- 610 Tsubokura, M., Nakashima, T., Kitayama, M., et al. (2010). Large eddy simulation on the
611 unsteady aerodynamic response of a road vehicle in transient crosswinds. *International
612 Journal of Heat and Fluid Flow*, 31(6), 1075-1086. doi:
613 10.1016/j.ijheatfluidflow.2010.05.008
- 614 Zaidi, H., Taiar, R., Fohanno, S., et al. (2008). Analysis of the effect of swimmer's head position
615 on swimming performance using computational fluid dynamics. *Journal of Biomechanics*,
616 41(6), 1350-1358. doi: 10.1016/j.jbiomech.2008.02.005

617 Zhang, D. Y., Zheng, W. T., Ma, Q. Z., et al. (2009). Numerical Simulation of Viscous Flow
618 around Rowing Based on FLUENT. *2009 Isecs International Colloquium on Computing,*
619 *Communication, Control, and Management, Vol I*, 429-433.
620