Abstract

While riding cycles, cyclists usually experience an aerodynamic drag force. Over the years, there has been a global effort to reduce the aerodynamic drag of a cycle. Fenders affect the aerodynamic drag of a cycle to a large extent, and fender coverage has a pronounced effect on the same. In this article, various fender coverage angles, varying from 60° to 270°, were studied to predict the aerodynamic drag with the help of a validated CFD model in SolidWorks Flow Simulation. The model was based on the Favre-Averaged Navier-Stokes (FANS) equations solved using the k-ε model. It was predicted that aerodynamic drag coefficient reduced fender coverage angle up to 135°, and thereafter started increasing. Analyses were carried out at velocities of 6 m/s, 8 m/s and 10 m/s and the results were found to be similar, with a minimum aerodynamic drag coefficient at 135° occurring in all the cases under study. There was an observed optimum decrease in drag coefficient to the extent of 4.6%, 4.5% and 4.6% as compared to the bicycle without fenders for the 6 m/s, 8 m/s and 10 m/s cases, respectively.

Keywords

Bicycle, CFD, aerodynamic drag

Introduction

In the modern age, sports are becoming more and more competitive day-by-day. To achieve such a level of competitiveness, sportspersons are continuously striving to improve their existing levels of performance. In order to achieve this, there is an incessant need for improved techniques, equipment and accessories. There are physical limitations beyond a certain level of performance achieved by athletes. Engineering could help them by providing equipment which can improve their performance.

A number of sports involve the motion of the athlete, the equipment or both. Motion is inevitably followed by a disturbance in the surrounding medium. Sports like cricket [1], soccer [2, 3], baseball [4], swimming [5] and badminton [6] rely greatly on aerodynamic phenomena. As in the aforementioned sports, in cycling, too, aerodynamic phenomena play a prominent role. The speed of the cycle and the power expended by the rider are limited by the physical ability of the rider. In order to reduce aerodynamic drag and increase the efficiency of the rider, cycle structures and accessories may be designed. Fenders in a bicycle are accessories primarily used for the purpose of protection of the cycle and cyclist from mud and dust, but in addition, the aerodynamics of the cycle is also affected. Computational fluid dynamics (CFD) is an engineering tool which uses numerical and computational methods in the analysis of fluid flow phenomena. For sports in which such phenomena are involved, CFD can be used in the analysis and development of equipment.

Aerodynamic drag increases with an increase in travel speed of the bicycle. Debraux et al. [7] established that travel speeds greater than 14 m/s creates an aerodynamic drag that accounts for more than 90% of the total resistive force experienced by the cycle. Zdravkovich et al. [8] experimentally analysed the effect of shape factor, i.e. the ratio of wheel-to-tyre diameter and found that an increase in the same increases aerodynamic drag considerably. Zdravkovich et al. and Sayers et al. [9] conducted experimental analyses on the effect of wheel rotation on the drag of the bicycle and concluded that the introduction of cladding resulted in a prominent reduction in aerodynamic drag.

Doval et al. [10], Gibertini et al. [11] and Blocken et al. [12] worked on the effect of the rider position on the aerodynamic drag, with various positions such as upright, dropped and time trial. Due to the change in the frontal area of the cycle and cyclist, the time-trial position was found to be the most aerodynamic.

Cycling accessories, particularly helmets, have also been subjects of research. Alam et al. [13] conducted aerodynamic and thermal analyses of various commercially available cycling helmets based on their design and venting position.
Chabroux et al. [14] analysed the effect of helmet inclination on the drag coefficient in the time-trial position. They concluded that natural helmet inclination is associated with the greatest decrease in the drag coefficient. Beaumont et al. [15] conducted a study of time-trial helmets using CFD and concluded that variation in head position and helmet shape had a considerable influence on aerodynamic performance.

Fender coverage angle of a bicycle plays an important role on the effect of various fluid dynamic parameters. Going through literature available, it is observed that work on the fender coverage angle of a bicycle is negligible. Hence, there is an urgent need to study the effect of fender coverage angle on such parameters. This article is an attempt in this direction. This study is designed for the analysis of a city bicycle, typically used for moderate distances in urban areas. Such bicycles usually contain fenders [16, 17, 18]. Fender coverage angle has been studied in order to predict frontal area, drag force and drag coefficient as a function of air velocity.

**Methodology**

This article includes computer-aided design (CAD) modelling, mesh generation and three-dimensional (3D) CFD analysis. The flow modelling was further analysed against various possible grid-independent tests and reported data. The validated model was further used to perform parametric studies.

**CAD Model of the Bicycle and Rider**

A 3D CAD assembly of the bicycle, rider (a female of height 1778 mm and weight 70 kg), as shown in Figure 1, and a solid plane under the bicycle were created using SolidWorks and Autodesk Fusion 360. The rider is wearing a helmet. The various components are shown in Figure 2. The bicycle is further divided into five components, which include the bicycle frame created in accordance with the dimensions of a standard city bicycle, the wheels (two nos.) and the fenders (two nos.). The fenders were located on both the front and back wheel of the bicycle and were symmetric about axes perpendicular to the solid plane. The axes were passing through the centre of each of the wheels.

The frontal areas of various CAD models were computed with the help of SolidWorks. The values of the frontal area of various models are plotted as a function of fender coverage angle in Figure 3.
Numerical Approach

Figure 4 shows the algorithm which was used for predicting various parameters such as drag force and drag coefficient. The input parameters and goals defined are listed in Table 1. Convergence was monitored and analysis was terminated when goal residuals reached the order of $10^{-6}$. When convergence was achieved, the results of the current analysis were plotted and the next model was chosen for analysis.

The computational domain was chosen to be a cuboid of length 32 m, height 8 m and width 8 m, as shown in Figure 5, in accordance with best practice guidelines [19]. An external analysis was conducted using the 3D steady Favre-Averaged Navier-Stokes [20] equations solved with the $k$-$\varepsilon$ model [21] with second-order accuracy.

Defraeye et al. [22] studied and validated the aerodynamics of a cyclist using various turbulence models and found that the $k$-$\varepsilon$ model predicted the aerodynamic drag most accurately as compared to the corresponding wind tunnel result. Based on these results, the $k$-$\varepsilon$ model was chosen for the present study.

The following boundary conditions were imposed in order to simulate the travel of the bicycle on a road. The road was taken as a non-slip moving wall. The dimensions of the domain under study were taken as $32 \times 8 \times 8$ m, the cycle was termed stationary and the air was input at 6, 8 and 10 m/s. The wheels were given a rotational velocity equal to the velocity of the moving wall. Ambient pressure and temperature was imposed.

Equations 1 and 2 were utilized for the calculation of the coefficient of drag and lift, respectively, which were the reported quantities in the analysis.

\[
C_D = \frac{F_D}{\frac{1}{2} \rho A_D v^2} \quad \text{Eq. (1)}
\]

where $C_D$ represents the drag coefficient, $F_D$ represents the drag force, $\rho$ represents the density of air, $A_D$ represents the frontal area normal to the direction of travel and $v$ represents the relative velocity of travel of the bicycle with respect to air.

\[
C_L = \frac{F_L}{\frac{1}{2} \rho A_L v^2} \quad \text{Eq. (2)}
\]

where $C_L$ represents the lift coefficient, $F_L$ represents the lift force and $A_L$ represents the frontal area parallel to the road.

SolidWorks uses the Cartesian method for the meshing of solid models. Cartesian grids have been observed to be trivial in terms of computational resources required, alongside yielding results of comparable quality to those of other more complex grid systems [23]. In the flow simulation module of SolidWorks, the ratio factor quantifies the fineness of the mesh, with a higher ratio factor representing greater fineness in the section containing the CAD model. The grid-independent tests [24] were now carried out in order to choose the required grid fineness for the parametric study. When results showed mutual agreement over a number of consecutive ratio factors, the grid fineness was fixed. The mesh used for analysis is depicted in Figure 6. It is evident from the figure that the region close to the cycle has a greater mesh density than the
part of the domain that does not contain the CAD model. Furthermore, as the distance from the cycle increases, the cell size is observed to increase, and mesh density correspondingly decreases. Regions of greater model complexity such as the wheels and the model boundary are observed to have the greatest mesh density.

The boundary layer was captured effectively by maintaining the average $y^+ < 5$, across analyses. After the initial solution was obtained, the $y^+$ value was adjusted by increasing the fineness of the mesh close to the walls. This was done in order that the simulation of fluid flow close to boundaries was efficient and natural and to produce accurate results. The $y^+$ was adjusted by varying the initial mesh level as well as the ratio factor used in the meshing settings. The initial mesh level was set to a maximum value of 7 and a grid-independent test was carried out in order to determine the optimum ratio factor.

Table 2 contains the setup conditions used for analysis.

Further parametric study was now carried out in order to find the effect of fender coverage angle on the drag force and drag coefficient. This was done by varying the fender coverage angle of the cycle under the same boundary conditions as applied earlier.

The fender coverage angle was varied between 60° and 270° at a difference of 15° between two consecutive analyses. These results were compared with the results for a cycle without fenders. The effect of velocity was also studied by varying the velocity from 6 m/s to 10 m/s.

### Grid-Independent Test

The grid-independent test was performed for the model under consideration. The analyses were performed on nine equidistant line segments on the centre plane of the rotating region of the front wheel of the bicycle, perpendicular to the solid plane. One centre line segment lies on the axis passing through the centre of the wheel, and four line segments each lie on either side of it. Each line segment contains 11 points for analysis based on geometric distribution. The points are shown in Figure 7.

The test was carried out on a number of different grids for the present study. The analysis was conducted on grids of

### Table 2 Analysis setup values.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
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<tbody>
<tr>
<td>Level of initial mesh</td>
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<tr>
<td>Advanced channel refinement</td>
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<td>Ratio factor</td>
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<td>Gravity</td>
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<tr>
<td>Rotation</td>
<td>On</td>
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<td>Analysis type</td>
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<td>Air</td>
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<tr>
<td>Flow type</td>
<td>Laminar and turbulent</td>
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<tr>
<td>Turbulence parameters</td>
<td>Turbulent energy and dissipation</td>
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<td>Pressure</td>
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</tr>
<tr>
<td>Temperature</td>
<td>293.2 K</td>
</tr>
</tbody>
</table>
ratio factor 8.5, 9, 9.5 and 10 at an initial mesh level of 8 with the \( k-\varepsilon \) model. The number of cells in the four meshes varied from \( 4 \times 10^6 \) to \( 5 \times 10^6 \).

The velocity in the direction of travel \((v)\) was plotted with the dimensionless quantity \( Y/Y_{\text{max}} \), where \( Y \) is the \( Y \)-coordinate of the point under consideration from the origin assumed at the centre of the wheel and \( Y_{\text{max}} \) is the maximum \( Y \)-coordinate of the wheel for the line segment under study. All four meshes showed considerable mutual agreement. For brevity, the results of two grid-independent tests are shown in Figure 8. The mesh with ratio factor 8.5 was hence chosen for further analysis.

### Validation

The results of drag area \((C_D A_p)\) obtained by the current computational model were validated against reported data of Zdravkovich et al. [25] and Defraeye et al. [26]. The CFD results for the model with no fenders were found to be in good agreement with the mean drag area calculated by Zdravkovich et al. as well as by Defraeye et al. in wind tunnel experiments. The results are summarized in Table 3.

Further validation was carried out by comparing the given results with experimental results obtained by Barry et al. [27], who analysed the impact of yaw angle on the drag area of a bicycle with a rider. The experimental study was carried out at 50 km/h, and the wheels and geometry used were similar to those used in the current study. The physical conditions of the experimental study were simulated in the current numerical model, and the results were observed to be in close concordance, as is evident from Figure 9.

### Results and Discussion

Analysis was carried out to predict parameters such as drag force and drag coefficient as a function of fender coverage angle of a bicycle for constant velocity. Figure 10 depicts the analysis with 240° fender coverage angle at a velocity of 10 m/s. The results are presented under Figures 11 and 12.

Figure 11 represents drag force in Newton as a function of fender coverage angle \((\theta)\). It is evident from the graph that drag force for all velocities under consideration has shown similar trends. The drag force is seen to initially decrease with increase in fender coverage angle from 60° to 120°. This is true for all cases of bicycle velocity under consideration for the present work, such as 6, 8 and 10 m/s. Sayers et al. [9] conducted an experimental analysis of rotating racing cycle wheels and observed that wheels with spokes exhibited a considerably greater drag coefficient than wheels in which the spokes had been covered. This effect was attributed to flow separation around the cycle wheels, which prevented the wheels from creating eddies as the wheel rotates, reducing drag. The addition of fenders in front of bicycle wheels also creates a zone of flow division, which reduces the creation of eddies on the rotation of the wheel, leading to a reduction in the drag force.
For a further increase in fender coverage angle, the drag force is seen to increase. The increase in drag force is moderate till 165° and increases sharply beyond 165°. The value of drag force stays below the drag force calculated for a cycle without fenders in the range 60°-190° coverage angle for the 10 m/s case. This range decreases marginally as the velocity is reduced.

After the minimum value of drag force is reached at 120°, the increase in the drag force for fender coverage angle beyond 120° indicates that the increase in profile drag due to increase in the frontal area over consecutive values of fender coverage angle is greater in value than the reduction in drag due to the aforementioned flow separation. Due to the same reason, the increase in fender coverage angle eventually begins to have a detrimental effect on the drag force of the cycle and cyclist, and increases to values greater than in case of no fenders.

It is evident from Figure 12 that drag coefficient for air velocity 6 m/s, 8 m/s and 10 m/s shows similar trends. The drag coefficient decreases in the initial stage with increase in fender coverage angle from 60° to 135°. For fender coverage angle 135° and 165°, drag coefficient increases, but the marginal increase with increase in angle is to a lesser extent. Beyond a fender coverage angle of 165°, drag coefficient increases abruptly upward. This corresponds to a similar upward increase in the frontal area, which in turn increases the drag force, and hence the drag coefficient. For any particular fender coverage angle, drag coefficient decreases with an increase in velocity from 6 m/s to 8 m/s. Moreover, the drag coefficient decreases further from 8 m/s to 10 m/s. This follows research conducted by Grappe [28] as reported by Debraux et al. [7], where it was observed through wind tunnel experiments that the drag area (ACD) decreased with increase in velocity in the velocity range taken up by the current study. This value of drag coefficient remains below the computed value for a cycle without fenders from 60° to 215° in the 10 m/s case, and this range is seen to be similar for all three velocities.

It is evident from Figure 13 that there is a notable decrease in the turbulence intensity behind the wheel region for the bicycle with fenders as compared to the bicycle without fenders. The rotation of wheels with spokes leads to the creation of turbulent eddies behind the wheels, which leads to the creation of a low-pressure region. This low-pressure region leads to an increase in the drag force experienced by the cycle. The introduction of fenders divides the flow of air in the region in front of the wheels, leading to a considerably lower volume of air coming into contact with the spokes. This leads to a reduction in the turbulent eddies created, thereby leading to a reduction in drag.

Figure 14 summarizes the change in drag force, and Figure 15 summarizes the change in drag coefficient as compared to values for the cycle without fenders. It is observed in the figures that the percentage change in both drag force and drag coefficient follows similar trends, with there being minimal difference with change in velocity. The magnitude of change in drag force is seen to vary from a decrease of 3.5% to an increase of 5.8%, while the magnitude of change in drag coefficient varies from a decrease of 4.6% to an increase of 2.2%.
For all three cases, the maximum reduction in the drag coefficient is observed at 135° fender coverage angle. The maximum reduction in drag coefficient for the 6 m/s, 8 m/s and 10 m/s case is calculated as 4.6%, 4.5% and 4.6%, respectively. These values are tabulated in Table 4.

All the three cases imply that the addition of fenders to the cycle frame around the wheel results in a reduction of drag force experienced by the bicycle and the cyclist. The reduction of more than 4.5% in each case, with the optimum reduction of 4.6% indicates a significant improvement in the performance of the cyclist and the design of the bicycle. Furthermore, these reductions also imply a reduction in the effort required by the cyclist per unit distance as well as a reduction in overall time required per unit distance.

While the current study elaborates on the impact of fenders on the aerodynamic drag of bicycles, a wide scope exists for further research in the field. Future subjects of study may include experimental and computational analyses of parameters such as the fender shape, profile and width, which may also have an effect on the aerodynamics of bicycles. Further accessories such as claddings and discs may also be tested.

### Conclusion

Through 3D CFD simulations conducted using SolidWorks Flow Simulation, the impact of fender coverage angle on the aerodynamic drag on a cycle and cyclist was analysed. The principal conclusions of the analysis are as follows:

- In analysis performed at symmetric fender coverage angles from 60° to 270° at velocities of 6 m/s, 8 m/s and 10 m/s, the drag force as well as drag coefficient were...
shown to initially decrease with increase in fender coverage angle, and then increase.

- The creation of flow division at lower values of fender coverage angle reduces the creation of eddies, thereby reducing drag. However, as this angle increases, the profile drag increases, leading to an increase in drag.
- This implies that there is an optimum fender coverage angle, which leads to the greatest value of aerodynamic drag reduction in the bicycle.
- A fender coverage angle of 135° is found to produce the best results for reduction in drag coefficient in all three cases.
- The maximum computed reduction in aerodynamic drag coefficient as compared to the case without fenders is 4.6%, 4.5% and 4.6% for the 6 m/s, 8 m/s and 10 m/s case, respectively.
- The percentage change in drag force and drag coefficient as compared to the cycle without fenders is seen to be invariant with change in velocity.
- It is also observed that the drag remains less than the case for no fender for a wide range of angles.
- This study confirms the positive effects of the addition of fender on the aerodynamic drag of a cyclist riding a cycle.

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Nomenclature

\( \rho \) - density of the medium

\( t \) - time

\( u_i \) - velocity of flow in the \( x_i \) direction

\( u_j \) - velocity of flow in the \( x_j \) direction

\( P \) - fluid pressure

\( \tau_{ij} \) - shear stress tensor

\( S_i \) - body force

\( C_D \) - drag coefficient

\( F_D \) - drag force

\( A_D \) - frontal area normal to the direction of travel

\( v \) - relative velocity of travel of bicycle with respect to air

\( C_L \) - lift coefficient

\( F_L \) - lift force

\( A_L \) - frontal area parallel to the road

\( \theta \) - fender coverage angle

Subscript

\( i \) - direction

\( j \) - direction

\( e \) - energy

\( L \) - lift

\( D \) - drag

References