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Assessing aerodynamic performance in cycling using computational fluid dynamics

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ABSTRACT: Aerodynamic resistance is one of the leading challenges to overcome in elite cycling. To optimize cycling aerodynamics, estimates must first be made by means of wind tunnel testing, computational fluid dynamics or track testing. Computational fluid dynamics (CFD) is an emerging field in analysing cycling aerodynamics. Wind and urban physics create conditions difficult to model in a wind tunnel environment, and while physical track and/or velodrome testing occurs in actual cycling environments, it is difficult to control and quantify all influencing environmental factors. CFD allows for complete control over all model parameters. It also allows for controlled flow conditions to quantify small aerodynamic performance improvements through changes in athlete posture/equipment along with extensive measurement capabilities. Modelling cyclists and other vulnerable road users in urban environments can complement urban designs and strategies to enhance pedestrian/cyclist safety in high wind conditions. Additionally, modelling the aerodynamics of bluff body objects such as a cyclist's body follows a similar procedure to modelling the airflow over complex structures. This paper presents not only an in-depth survey of existing CFD research on cycling aerodynamics and its impact on the cycling community, but also highlights gaps in knowledge regarding cycling aerodynamics and suggests a methodology for future research to follow.

KEY WORDS: Urban Physics; Aerodynamics; Computational Fluid Dynamics; Wind tunnel; Cycling.

1 INTRODUCTION

There are several different resistive forces affecting the performance of cyclists; aerodynamic resistance, road gradient, rolling resistance, drive train and wheel bearing resistance. However, aerodynamic improvements, particularly on flat to rolling terrain, offer the greatest potential for improvements in cycling speed [1]. For example, at speeds in excess of 50 km/h the aerodynamic resistance is up to 90% of the total resistance experienced by the cyclist [2]. It is evident over the history of cycling, that significant performance gains have been made, primarily due to the advancement of technology and the understanding of the underlying physics. For example, a performance improvement index was developed by Haake [3], to allow for comparison between athletes, and for a comparison between sports; a higher index indicating a greater improvement in the sport. The results for cycling are impressive, with a 221% increase in the International Cycling Union (UCI) one-hour track cycling record over 111 years. Furthermore, the 4-km individual pursuit improved by 35% over 32 years.

Studying the flow field around a cyclist can be challenging. Performing smoke tests in a wind tunnel can shed some light on the complex flow interactions. However, wind tunnel testing often presents aerodynamic improvements solely through evaluating drag reduction, as detailed flow fields can be difficult to obtain [4]. Computational fluid dynamics (CFD) tools can be a useful asset to study whole flow field data. CFD provides the ability to analyse the wake flows of athletes; thus, identifying the causes of drag. The benefits of CFD are now being widely recognized within the cycling industry. The use of CFD tools is also well established within motorsport. Other elite sports such as swimming, skiing, bobsleighs and to some extent running have also embraced its potential [5]–[8]. Olympic gold medals can be won by tenths of a second [7], and it is possible to use CFD to realise aerodynamic enhancements which lead to additional speed or time savings. Advances over the past two decades in computer hardware have had positive impacts on the utilisation of CFD for sports aerodynamics research, from motor sport applications to summer and winter Olympic sports [9]. A key aim of aerodynamic testing is discovering new cycling positions that conform to the UCI rules while providing aerodynamic benefits. Similar procedures have been found to be successful in other sports such as bobsleigh aerodynamics. Computational modelling in bobsleighs on the positioning of the internal crew members yielded significant aerodynamic benefits without breaching regulations [6].

2 CFD METHODOLOGY FOR CYCLING

CFD has become one of the greatest assets in understanding cycling aerodynamics in recent years. Detailed flow-field information can be attained along with drag force detail on individual components. Defraeye et al. [4] assessed the accuracy of CFD for cycling applications. A scale model of a cyclist was used to validate CFD models using wind tunnel experiments. In addition to three-component forces and moments, high-resolution surface pressure measurements were taken from the scale models surface at 115 locations, which provided detailed information on the flow field. The data provided from the wind tunnel tests are used to compare the performance of several Reynolds-Averaged Navier Strokes (RANS) turbulence modelling techniques, large-eddy simulations (LES), and low-Reynolds number modelling (LRNM) and wall functions for boundary layer modelling techniques. The RANS shear-stress transport (SST) k-ω model provided the best overall performance, followed closely by LES. LES provides valuable transient information but at a high computational cost. Furthermore, the additional temporal sensitivity analysis that is required makes LES less attractive for practical calculations. LRNM held the best performance to model the boundary layer in comparison to wall functions. Only the rider was modelled in this research, with high resolution 3D scanning providing the geometrical information required.

Drawn on previous best practices, Figure 1 proposes a methodology for the aerodynamic analysis of sports equipment and athletes using CFD. This methodology also is applicable to various urban physics fluid related problems.

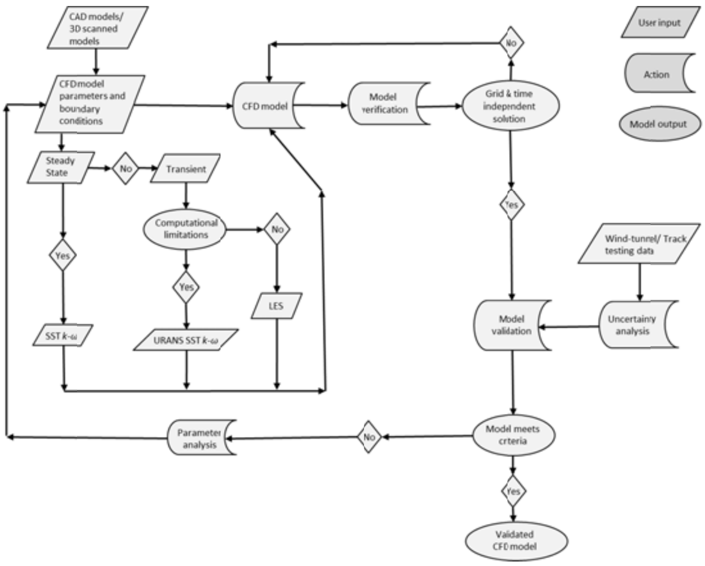

Figure 1. A proposed flowchart methodology for aerodynamics analysis of cycling using CFD.

3 WINDTUNNEL VALIDATION METHODS FOR CFD MODELS

Wind tunnel testing can provide aerodynamic drag and moment characteristics as well as providing opportunities for flow visualization. A multi-component force sensor is used to determine the drag and additional yaw forces and moments acting on the cyclists. Wind tunnel testing can be relatively expensive and requires further investment where flow visualization is required. Flow visualization techniques can yield information on why different cycling positions generate less drag, providing a means to further lower the drag profile of a cyclist. There are various methods available for flow visualization in wind tunnel testing, smoke tests being the most common. Oil and ink flow methods are also common. Crouch et al. [10] demonstrated how aerodynamic drag can be assessed from the perspective of the fluid through which the cyclist moves. Such techniques provide more information regarding how drag forces are generated. Crouch et al. [10] also studied the evolution of the wake around the crank cycle using a quasi-steady approach in wind tunnel experiments, discovering that the dominant mechanism affecting large variations in drag from the rider's legs is not the variation in the frontal surface area over the pedal stroke, but the large change in the flow structure over the crank cycle [10], [11]. It was concluded that there is the potential to improve rider aerodynamics through a targeted approach at reducing the drag associated with the vortices flow structures developed from locations on the rider's body. This research utilized various wind tunnel flow visualization techniques such as a series of detailed time averaged velocity field wake surveys, skin friction flow visualizations, wool tuft flow visualizations, and time averaged surface pressure measurements for varying leg positions.

Chowdhury et al. [12], [13] developed one of the most recent full scale testing methodologies for the measurement of aerodynamic properties as a function of cyclist's body positions along with various cycling accessories under a range of air flow velocities. Both static and dynamic testing can be performed using this methodology in a suitable wind tunnel. A six-component force sensor under the platform provides force and moment measurements. Repeatable crosswind testing may be conducted with the aid of a camera system for consistent athlete posture positioning. A drawback of this methodology however is the lack of loaded rotors to provide a set resistance to the cyclist under dynamic testing conditions, along with the inability to transfer the rotation to the front wheel, which has been widely used elsewhere in the literature [14]–[16]. García-López et al. [17] addressed the sensitivity of aerodynamic drag in wind tunnel testing with recommendations for future research which is applicable to other researchers. These include pedalling at a race pace to adequately represent the mean power maintained over the course of the event. The front wheel should be allowed to rotate at the same pace as the rear wheel. The bicycle should be fixed to a valid power meter that allows lateral movement of the bicycle-cyclist system, and synchronization of the force balance and the bicycle's crank. The system used by Defraeye et al. [18] is presented in Figure 2. A methodology for wind tunnel testing is presented in Figure 3 which is also valid for other civil applications.

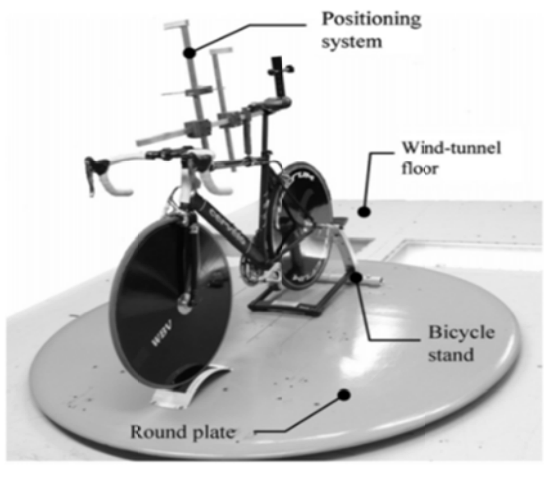

Figure 2. Cyclist and bicycle setup for wind tunnel experiments [18].

Corrections for blockage, due to the wind tunnel cross sectional area being too small relative to the frontal area of the test object, must be taken into account where required. Solid blockage is an important parameter for the validity of wind tunnel data. The walls of the wind tunnel can compress the streamlines and increase the velocity of the fluid over the test object [19]. This local speed is thus higher than the reference wind tunnel speed causing inaccuracies with aerodynamic coefficient calculations. The blockage ratio in Equation 1 determines if blockage corrections are required. A_t is the frontal area of the test item, and A_{wt} is the cross sectional area of the wind tunnel test section. Typically correction is required if the blockage ratio is greater than 7.5-10%. A complete methodology for blockage correction is found by Mercker & Wiedemann [19]. The drag area (C_DA) is presented in Equation 2. This is the typical reference value used for comparison and drag reduction purposes [20]. F_D is the axial aerodynamic drag force, ρ is the air density, V is the air velocity, A is the frontal area, and C_D is the drag coefficient.

$$BR = \frac{A_t}{A_{wt}} \quad (1)\ [22]$$

$$C_DA = \frac{F_D}{\frac{1}{2}\rho V^2} \quad (2)\ [21]$$

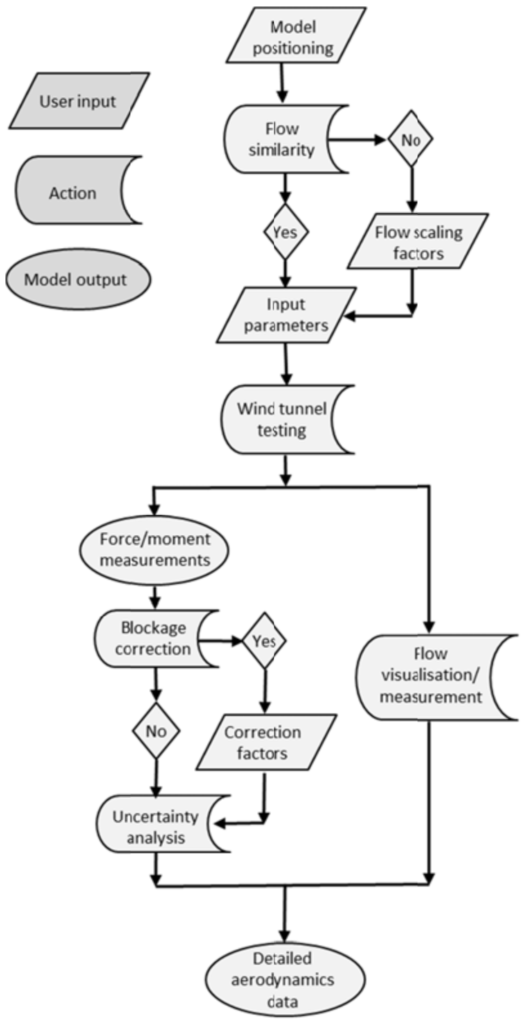

Figure 3. A proposed flowchart methodology for wind tunnel analysis of cyclists and bicycles.

4 CYCLIST AERODYNAMICS MODELLING WITH CFD

Fintelman et al. [23] used validated CFD models to investigate the flow field around a static cyclist at various yaw angles. RANS simulations (k-ε and SST) were used to analyse various yaw angles, while detached-eddy simulation (DES) and LES were used to analyse only a single yaw angle of 15° due to their increased computational expense. The bicycle was included in the simulation along with the rider, with simplified geometry with features such as the nose, lips, bicycle spokes and cables being neglected. A standard urban helmet was used instead of an aerodynamic TT helmet as this research is focused more at cycling safety than aerodynamic performance. Discrepancies between different CFD modelling techniques and the wind tunnel results were apparent with 17% difference in drag force between LES and experimental results at a yaw angle of 15°. Geometrical simplifications in the CFD along with interference drag from the wind tunnel test stand could be contributors to these discrepancies.

Defraeye et al. [18] studied three common cycling postures using CFD, those postures being standard upright position, dropped position, and time trial position. From the LES simulation of the cyclist alone without the bicycle, the drag area (m^2) of each position was 0.219, 0.172 and 0.142 respectively. These results confirm that a reduction in the frontal area of cyclists significantly reduces their drag area. It is further proved that the aerodynamic drag of the cyclist is 60-70% of the total drag experienced by the rider and bicycle combined.

CFD has been used to yield new insights into the phenomena known as drafting in the cycling world. Blocken et al. [24] made several new observations regarding drafting in cycling with the first published CFD simulations of drafting supported by wind tunnel validation. These included that the presence of the trailing cyclist reduces the underpressure at the back of the leading cyclist, yielding a drag reduction for the leading cyclist. Two cyclists were used in both the wind tunnel and CFD testing. However, only the riders were modelled in the CFD tests with the drag area of the stand and bike being taken away from the wind tunnel test results for comparability. Interference drag was also neglected.

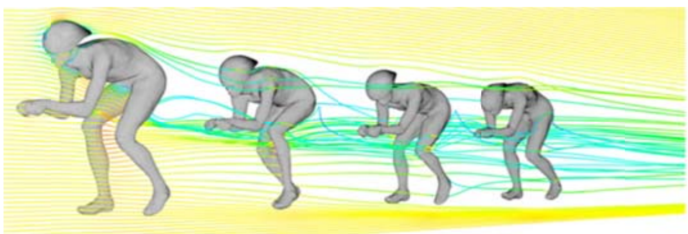

Figure 4. Streamlines of the airflow around four drafting cyclists [25].

Defraeye et al. [25] followed up on the research by Blocken et al. [24] further investigating the drafting phenomena using four individual cyclists, each 3D scanned and modelled in different racing positions. Thus team drafting was analysed with variations in individual positions, e.g. upright position for the leading cyclist and other variations.

Such research using numerical studies on cyclists in a pace line is extremely useful for determining an optimal cyclist sequence for time trial events both on the road and in velodromes. It was made clear that the drag of a cyclist is dependent on their position in the pace line. Second and subsequent positions experience drag reductions up to 40% in comparison to a single cyclist not partaking in drafting, with the second from last cyclist receiving the largest aerodynamic benefit from the formation.

Blocken & Toparlar studied other areas including the aerodynamic effects of a trailing car on the drag of a single cyclist (Figure 5) [26]. Both a static bicycle and rider were modelled in this simulation, but with some geometrical simplifications. A 3D scanned cyclist was physically modelled at a reduced scale for wind tunnel validation studies. The standard k-ε turbulence model was used with wall functions used instead of low Reynolds number modelling. The results show a 3.9 second impact on a 50 km time trial event. Thus following from the results of this research, Blocken & Toparlar recommend to the UCI that the 10 metre minimum distance rule should be altered to 30 metres to negate this aerodynamic benefit unknowingly availed of by some cyclists. It is noted that during actual races, the 10 metre limit is not strictly enforced and that there is at least one car, if not multiple, potentially influencing the drag of a cyclist.

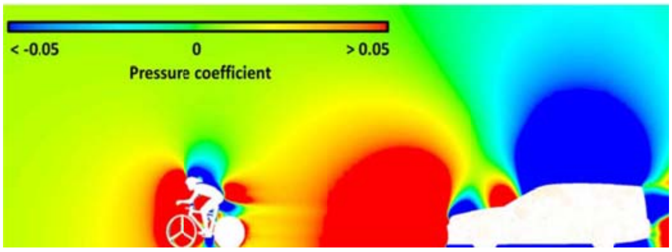

Figure 5. A pressure map of a trailing car on a cyclist [26].

The variation in drag force and associated downstream flow structure with crank angle was investigated numerically and experimentally by Griffith et al. [27]. CFD under-predicted drag measurements by 15% in comparison to wind tunnel experiments, however, the author put this partially down to the simplification of the geometry of the cyclists and bicycle. A good match of the downstream flow structure is found for the CFD and wind tunnel results. Minimum drag was observed at a crank angle of 15°, when the two thighs of the cyclist were aligned. The maximum drag is observed at a crank angle of 75°, when one leg is at full extension and the other leg is raised towards the rider's torso. The transient nature of the entire flow field was revealed by these CFD studies. Griffith et al. [27] concluded that the drag force experience by the rider depends on the surfaces to the rear and the downstream vortical flow structures associated with them. The strength of the vorticity structure can be linked to the drag force as shown by the alignment of either thigh perpendicular to the flow aggregating the power of downstream vortical structures. The author also indicates that caution should be exercised when modelling components isolated from the entire cycling geometry, as the positioning of the legs affected not only the drag force on the legs, but the drag force on the rider's torso.

5 WHEEL AERODYNAMICS MODELLING WITH CFD

In addition to simulating cyclist's aerodynamic performance using CFD, it has also been used to model the aerodynamics characteristics of wheels. Godo performed comprehensive aerodynamics research on a commercial bicycle wheel using CFD [28]. He presented a methodology for rapid and consistent aerodynamics studies on a range of bicycle wheel geometries under a large range of flow conditions. Ten different yaw angles were modelled at two speeds of 32 km/h and 48 km/h using steady state RANS analysis using the one equation Spalart-Allmaras turbulence equation. In addition to this, transient analysis using delayed detach eddy simulation (DDES) was run for five of the yaw angles at the same two speeds. This research allowed for flow structures to be identified and compared for different yaw angles and for the observation of a unique transition from downwards to upwards acting force as the yaw angle is increased. Viscous drag was found to be less than 3% of the overall force with the remainder of the force computed a result of pressure drag. The spokes generate a comparable drag to the wheel hub, with the tyre and rim generating the majority of the drag force.

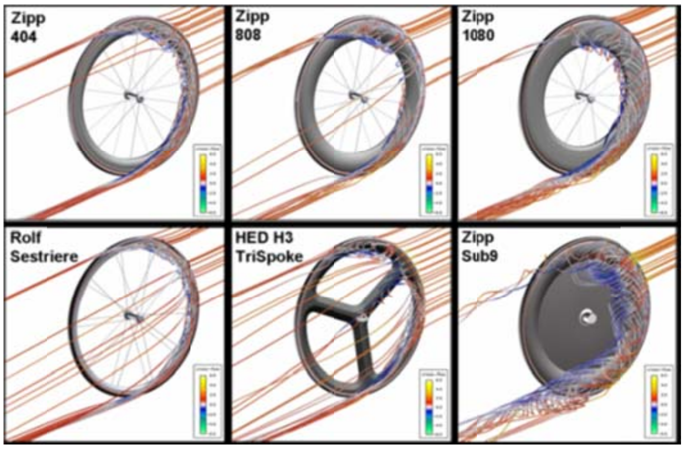

Figure 6. Streamlines at a yaw angle of 10° showing recirculation on the suction side of six different wheels [29].

Godo et al. [29] continued to build on their previous work using their methodology to analyse and compare six different wheels. Significant differences between the wheels were shown with deeper rim wheels offering a clear advantage under commonly experienced yaw angles (5-15°). Pogni et al. [30] also confirmed the satisfactory capability of CFD to describe the aerodynamic behaviour of bicycle wheels using steady state RANS simulations. Knup & Farmer further investigated the suitability of CFD for studying the aerodynamics of wheels [31]. Six different wheels were tested at varying yaw angles using steady state analysis with the k-ε turbulence model. The drag of a disc wheel was shown to decrease with increasing yaw angle, turning negative at 20°.

6 PARACYCLING AERODYNAMICS

While the racing bicycle for professional or casual use has experienced extensive development with regard to aerodynamics using CFD techniques, similar development has not occurred with regard to tandem cycles or hand-cycles that are used by elite para-cyclists. Hand-cycle design can be specific to the athlete involved due to variations in disability. Thus completely different positions can be used during the race depending on the cyclist, particularly in race phases such as a downward slope where the cyclist does not need to pedal and can adjust their position to minimize aerodynamic drag. Existing elite hand-cycles are a young technology with little aerodynamic research conducted to enhance their potential. The only available published literature to the best knowledge of this author is by Belloli et al. [15] who performed dynamic wind tunnel testing of two hand-cycle/rider combinations, an arm powered hand cycle, and an arm trunk powered hand cycle (Figure 7). A specialized system was built for the wind tunnel testing where the hand cycle is mounted on a support frame with each wheel placed on rollers with an adjustable resistance.

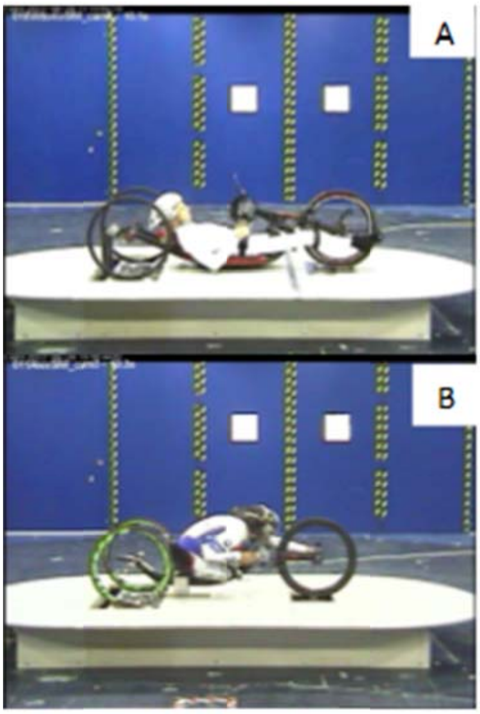

Figure 7. An arm powered hand-cycle (7a), and an arm trunk powered hand-cycle (7b), both in aerodynamic postures [15].

7 DISCUSSION/CONCLUSIONS

There are numerous gaps present in current knowledge of cycling. Firstly, bicycles and their riders are rarely modelled together using CFD due to the computational expense. Thus, interference drag between the rider and the bicycle is neglected if one or the other is left out [18, 24, 32]. When validating CFD simulations against wind tunnel data, the drag area of the bicycle is subtracted from the wind tunnel measurements to give comparable data to the CFD results. This further neglects interference drag however leading to possible discrepancies within results. When athletes and their bicycles are modelled together, numerous simplifications are made to the model to reduce computational expense. For example, the spokes and cables on the bike are often neglected and the finer details of the cyclist such as facial features are also neglected [26]. A drawback of CFD is its current inability to model the varying roughness on riders TT suits. LRNM and wall functions have been used in the past to model the surface of the rider, with little or no difference between the skin, suit and helmet surface modelling [24, 26, 33]. Wall functions allow for some roughness to be taken into account; however they assume certain flow conditions without actually solving the viscous sub-layers at the surface geometry, as is the case with LRNM.

Dynamic simulations using CFD have not yet been utilized for cycling to the best knowledge of this author. Such instantaneous transient data of a pedalling cyclist would provide highly sought and valuable aerodynamics data to the cycling community. The ability to visualise the flow around a dynamic cyclist on the graphical platform CFD provides could prove invaluable. Some attempts have been made to graphically display flow patterns from a dynamic cyclist using experimental methods. Three dimensional flows around a full scale cyclist mannequin were investigated in pursuit of explaining the large variations in aerodynamic drag measured as the mannequins legs are positioned around the 360° crank cycle [10]. While this research provided a major leap forward in the current understanding of cycling aerodynamics, CFD analysis would supplement and extend research of this nature providing a broader and in-depth understanding of the complex dynamic flows on a platform readily accessible to most researchers. Hucho identified trailing streamwise vortices as a primary feature of vehicles wakes, having a large impact on the drag of a vehicle [34]. Crouch et al. found similar flow structures in the wake of cyclists and determined that future investigation into the wake of cyclists will have the largest impact on reducing the aerodynamic drag force [10].

The use of CFD in sport was reviewed by Hanna, covering a 20 year period, 1992 to 2012 [9]. While this paper focuses on motorsport and other sporting events, many of its conclusions and predictions are relevant for the cycling world. Virtual modelling of athletes in real time at competitive events is predicted, in an effort to gain competitive advantages on the day. Physically realistic CFD/multiphysics models of athletes are also predicted to virtually test new equipment or sports textile suited to individual athletes. A drawback of wind tunnel testing is the difficulty in obtaining whole flow field data. Wind tunnel studies commonly have investigated only the aerodynamic forces on the cyclist; however the research conducted by Blocken et al. [24, 26, 35] on cycling aerodynamics has utilised CFD to obtain whole flow field data, heavily validated by wind tunnel studies. This combination provides reliable aerodynamics results, yielding new insights into the wake flow of cyclists and the fundamental causes of aerodynamic drag. Some discrepancies remain between CFD simulations and their wind tunnel validation tests. Support structures are required for wind tunnel experiments of bicycles. These structures are not in place for the corresponding CFD studies. It is recommended by this author that CFD studies should initially mimic the wind tunnel validation tests to the best extent, and upon validation, the support structures can be removed from the model to give a clearer indication of the flow field around a cyclist.

Some wind tunnel analysis has been conducted on competitive hand-cycles [15], however there is no current knowledge or understanding of the flow around hand cycles, recumbents and tandems, despite a general agreement in the cycling world that recumbent type cycles are more aerodynamic than their upright counterparts [36]. Tandem cycling is all but untested in cycling aerodynamics to the best knowledge of this author. Research in this area has begun in NUI Galway in the form of a 4 year structured PhD programme. This new research will investigate the aerodynamics of paracycling using CFD, with a focus on tandem cycling. The present author gratefully acknowledges the funding provided by the department of Engineering and Informatics.

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