The understanding and development of cycling aerodynamics

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Abstract

In elite cycling the resistive force is dominated by aerodynamics. Be it on the roads or in the velodrome, the sport has many examples where aerodynamics has won and lost races. Since the invention of the bicycle, engineers have strived to improve performance, often by reducing aerodynamic drag. Over the last 50 years a number of authors have presented their efforts in journals, books and magazines. This review summarises the publications that show the continued development in the aerodynamics of cycling. The review concludes by examining the shortcomings of the current understanding and making suggestions for future research and development.

Keywords: aerodynamics, bicycle, cycling, drag, fluid dynamics, wind tunnel

Introduction and aim

The importance of reducing aerodynamic resistance in cycling has been recognised by engineers and cyclists for many years. There are many examples where superior aerodynamics has yielded a crucial and sometimes victorious advantage. One such example came in the 1989 Tour de France. Before the final stage, American Greg Lemond trailed the French leader Laurent Fignon by 50 seconds. All that remained was a 25 km individual time trial around the streets of Paris, just half an hour's racing. Lemond left the starting blocks with 'aerodynamic' tri-bars, an 'aerodynamic' helmet and a rear disc wheel. Fignon followed with no helmet, exposing his long hair to the air stream, and using the conventional time trial bars of the time. Lemond gained 58 seconds over Fignon on the day and won the tour by just 8 seconds, which today remains the smallest ever margin of victory in the race. We will never truly know for sure, but it seems that Fignon might have secured the race title if his choice of equipment had been more influenced by the most up-to-date engineering knowledge.

This review aims to summarise the notable developments and current understanding of the aerodynamics of cycling. The review will examine the publications that have furthered the understanding of cycling aerodynamics, after which some recommendations for future work will be presented. The governing fluid dynamic principles which dictate why some bodies have less drag then others shall not be presented here. If the reader is unfamiliar with concepts such as drag, streamlining and laminar and turbulent flow then publications by Whitt & Wilson

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(1982) and Kyle (2003) will be found both interesting and informative. It is also important to note the role that the governing body the Union Cycliste Internationale (UCI) has in controlling aerodynamic innovations. References shall be made to the limitations, but, if the reader seeks a comprehensive understanding of the rules, they are available on the Internet (www.uci.ch).

General cycling aerodynamics

One of the very first investigators of cycling aerodynamics was Nonweiler (1956 and 1958). The former work examined a cyclist in a racing position, i.e. holding the dropped handlebars, and found the drag coefficient was 0.93. The later work resulted in three conclusions: measurements of drag are repeatable to within ±3%; the subject's size and posture in the usual racing position have a relatively slight effect; and drag varies with the square of speed.

Pugh (1974) studied the oxygen consumption of six competition cyclists while they were cycling on an airfield. Comparative measurements were also made on an ergometer. The results were used to derive information about rolling and air resistance. It was found that the drag coefficient of bicycle and rider was 0.79, where the frontal area was determined from analysing photographs.

Prampero di *et al.* (1979) described an equation of motion of a cyclist. The experimental procedure involved towing two cyclists on racing bicycles in the dropped position. Tests were carried out in calm air and the cyclists were towed at a constant speed along a flat track. The investigation ran at different speeds (5 to 16.5 m s^{-1}), and from the results a relationship between resistive force (R_T) and air velocity (v) was found, $R_T = 3.2 + 0.19v^2$. It was assumed that the resistance at zero velocity (3.2 N) can be attributed entirely to rolling resistance, and the $0.19v^2$ term is the aerodynamic resistance. Therefore the constant 0.19 is equal to

$$\frac{1}{2}\rho C_D A$$

where is ρ the air density, C_D is the drag coefficient and A is the projected frontal area of the bike and rider. Frontal areas of cyclists in dropped racing positions range from 0.33 to 0.5 m^2 (Nonweiler (1956) and Davies (1980)). In accordance with the above study this gives a corresponding range of drag coefficients between 0.94 and 0.62, respectively.

Oxygen consumption when cycling against a range of wind speeds was studied by Davies (1980). Fifteen male cyclists were studied in a wind tunnel. They were required to pedal their bicycles at a set speed of 4.7 m s^{-1} on a motor driven treadmill against a headwind varying from 1.5 to 18.5 m s^{-1}. The subjects cycled for 8 minutes in the given conditions and the oxygen consumption was measured over the last 3 minutes of exercise. The results showed that, at constant treadmill speed, the oxygen consumption was proportional to the square of the wind speed. The results were used to calculate a drag coefficient of a bike and rider, which was found to be 0.56. This agrees reasonably well with the value calculated above (0.62) using the same frontal area (0.5 m^2).

In possibly the most in-depth study of the time Kyle & Burke (1984) researched a number of ways of improving a racing bicycle, focusing a lot of their efforts on reducing the aerodynamic drag. In the study, three prototype track bikes were produced as well as one road bike. They were evaluated in a wind tunnel and using coast-down tests. At speeds above 8 mile h^{-1} it was found that the wind resistance outweighs the rolling friction, and by 20 mile h^{-1} the aerodynamic contribution to drag is 90%. Therefore at racing speeds the contribution of aerodynamic drag is over 90%. It was also found that 31%–39% of the aerodynamic drag was due to the bike, depending on the rider position. This finding led Kyle and Burke to a simple three-tier hierarchy for reducing the cycling resistance: the rider position is most important, followed by the bike geometry and finally the rolling resistance. Kyle and Burke highlighted three ways of improving aerodynamic efficiency: lowering frontal area, streamlining the geometry and lowering the surface roughness.

A later study by Bassett *et al.* (1999) examined the power requirements of elite cycling and included a section outlining the factors that influence aerodynamic drag. A theoretical model for predicting the power required for track cycling was derived, which included the supposed aerodynamic performance of the different bicycles. Using the model, the world records for the distance travelled in one hour were compared. It was concluded that the rider who output the highest power was not Chris Boardman, the world record holder, but instead Tony Rominger, who holds the second fastest time. This conclusion again indicates the large influence improving a cyclist's aerodynamics may have.

Kyle (2003) presented the drag coefficient of a standard racing bicycle as 0.8 to 0.9.

Human powered land vehicles

In building a complete understanding of the aerodynamic development of bicycles it is worth mentioning human powered land vehicles. Because of the constraints placed on racing bicycle development by the UCI, splinter groups have been formed that choose to bypass these restrictions. The development of bicycles within these splinter groups will not be fully reviewed here, although if the reader wishes to find out more, Gross *et al.* (1983) and Kim (1990) make interesting reading. Owing to the unconstrained design ethos of this category, the bicycles that have been developed are weird and wonderful machines, the most advanced and fastest of which are fully covered by a fairing to greatly reduce losses. In 2000 a bike called 'Varna Mephisto' broke the world speed record, reaching a speed of 72.7 mile h^{-1}. This record was previously held by a bicycle appropriately called 'Cheetah', whose design and development was summarised by Ashley (1993). Incidentally, if the reader wishes to learn more about getting a bike approved by the UCI then Melton (1990) gives a good example of their intervention.

Rider position

As previously stated, Kyle & Burke (1984) found that rider position has the largest contribution to aerodynamic drag. As a consequence of this, further work has been done on studying different rider positions. Kyle & Burke also found that there was approximately 20% less aerodynamic drag when the rider was in a dropped position (the traditional time-trial position of the time). Aerodynamic drag was reduced even further, by 28% from the reference upright position, when the rider was in the hill-descent position (with hands in the centre of the handlebars, out of the saddle, straight legs and chin close to the handlebars). The four main cycling positions are shown in Fig. 1.

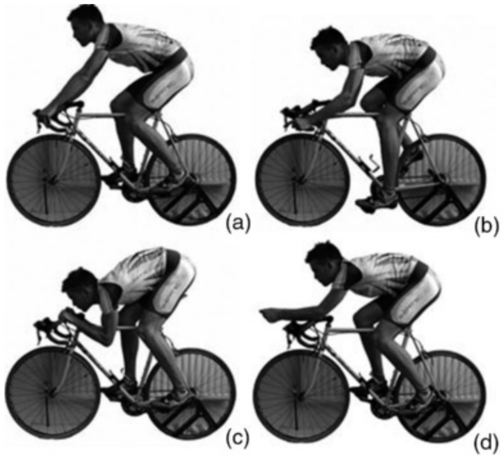

Figure 1 The four main cycling positions
(a) the traditional position, hands on brake hoods
(b) the dropped position, hands on drops, arms bent
(c) the hill descent position (d) the time trial position.

Kyle (1991b) reported on wind tunnel investigations carried out at California Institute of Technology in 1986. At this time tri-bars were not commercially available. Tri-bars allow the rider to rest their forearms on supports near the handlebar, creating a lower position with a greatly reduced frontal area (Fig. 1(d)). Kyle (1991b) investigated another position, which involved having the rider place their arms behind the seat, akin to a speed skating position. An aerodynamic chest support and modified steering behind the seat allowed this position. This position reduced the drag by 12%. Since the introduction of tri-bars development of this position has ceased.

Van Ingen Schenau (1988) quantified the effect of rider position to have a 1 km h^{-1} difference for every 10 degrees deviation from the optimum position, although the evidence to support this statement is somewhat lacking.

Kyle (1989a) conducted wind tunnel tests with bicycle manufacturers HED at the Texas A&M closed circuit wind tunnel. One aspect on the tests was to examine the use of tri-bars. The wind tunnel had a 2.1 by 3 m working section and a 6-component force balance. It was found that using tri-bars at 30 mile h^{-1} reduced the drag by 4.4 N compared with using the more conventional (at the time) 'cow-horn' handlebars, although the author stated that he thought the saving over traditional dropped handlebars would be more like 2.2 N. Different positions of the elbow rests were tested, revealing that, as the elbows were moved closer together, the drag decreased. It was also found that when the hands and forearms were level or tilted upward by 30° the drag was lowest. The drag increased when the bars were tilted up by 45°. With the arms flat, moving forward on the seat lowered the drag, however moving forward with the arms at 30° had little effect.

Lotus Sport developed a monocoque bicycle (Fig. 2(b)) that achieved high-profile success when Chris Boardman rode it to victory in the 4 km individual pursuit at the 1992 Olympic Games (Hill, 1993). The aerodynamics of the bicycle are discussed later, but some interesting conclusions were made about the rider's position on this bike. The optimum position on this bicycle was with the rider's arms and torso parallel to the ground, which is today's conventional time trial position. This position minimises the frontal area of the rider and also limits the interaction of flow around the rider and bike, ensuring that the air directly upstream of the bike is as undisturbed as possible.

A study by Richardson & Johnson (1994) examined the effect of cycling position using an alternative approach. In this study the effect of tri-bars on oxygen consumption was investigated. The hypothesis prior to the study suggested that, when a rider is cycling at a constant speed, the oxygen consumption would be less when using tri-bars, thus highlighting their aerodynamic advantage. This hypothesis was supported by a study by Johnson & Schultz (1990), who showed that there was no significant difference in heart rate, oxygen consumption, tidal volume, ventilation or mechanical efficiency when cycling on an ergometer using tri-bars. In the study by Richardson & Johnson the oxygen consumption of 11 cyclists cycling on level terrain at 40 km h^{-1} was measured. The cyclists used both normal handlebars and tri-bars in turn over a 4 km course, and oxygen consumption was recorded over the final 45 seconds of the run. The results of the study showed that the oxygen consumption was 2% lower when the riders used the aerodynamic handlebars. As their hypothesis predicted, the aerodynamic advantage of the tri-bars reduces the amount of oxygen required, thus proving the worth of handlebars of this type.

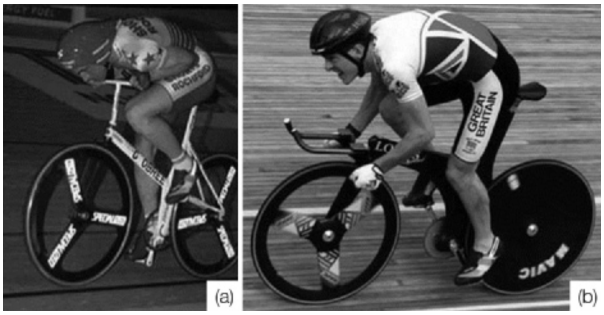

Figure 2 Graham Obree (a) and Chris Boardman (b) both had unique bikes that had a lasting influence on bike design throughout the 1990s

Broker (2003) presented work that was carried out on the USA National Team in 1995. This study examined the difference that subtle adjustments in rider position can have on aerodynamics. A 4000 m individual pursuit specialist was examined in a wind tunnel in two slightly different positions: first in the position he adopted towards the end of his event; and secondly when he lowered his head and extended and lowered his handlebars an inch in either direction. With a wind speed of 30 mile h^{-1} the former position gave a drag force of 23.57 N and the latter position 22.28 N, an improvement of 5.5%.

Another publication that shows continuing understanding of rider position, is the work of Zdravkovich *et al.* (1996). In this study two wind tunnels were used to investigate the flow around a full-scale and model bike, both with riders. It is worth noting that the larger wind tunnel, used for the full-scale model, was capable of speeds only up to 8 m s^{-1}, which is significantly less than professional racing speeds. The large wind tunnel also seemed to have significant blockage effects, although this was not quantified in the paper. These blockage effects suggest that the accuracy of the study may be questioned and should be considered when reviewing this work. The scale of the model and rider used in the smaller wind tunnel was 1:2.5. Using both experimental set-ups, six racing positions were tested. The position with hands on the centre of the handlebars gave very similar results to hands on brake hoods. Also the hill descent and time trial positions resulted in very similar drag values. Partly because of this, the position with the hands in the centre of the handlebars and the hill descent position were discounted. With the scale model, the four remaining positions were analysed. This showed that hands on drops (the lower part of a standard handlebar), with straight arms, was least efficient, followed by hands on brake hoods, then hands on drops with bent arms, then hands on tri-bars. The results from the full-scale tests agreed with this, showing that the most efficient position was with the rider using tri-bars, which gave a 17% reduction in drag from the upright position.

Grappe *et al*. (1997) studied the aerodynamic drag of different cycling positions including the position adopted by Graham Obree. His position was used in 1993 when he broke the prestigious world hour record, travelling a total distance of 52 713 m in one hour (Fig. 2(a)). Obree's position involves, like the time trial position, having the torso parallel to the ground. The hands however are not outstretched in front of the rider; instead they are tucked up tight against the chest and ribs. In this study measurements of drag were taken of 12 national and regional competition cyclists on their own bikes in the dynamic condition. Tests were performed in a velodrome in calm air (wind speed varied from 0.5 m s^{-1} to 1 m s^{-1}). The cyclists cycled around the velodrome, initially at 5 m s^{-1} then increasing their speed by 0.5 m s^{-1} for 12 laps. Pedalling was kept at 83 ± 12 rev min^{-1}, and tyre pressures were left at 7 bar for the entire study. The total resistance to motion was determined by measuring the average external mechanical power, using a simple device attached to the rear-wheel hub. The results showed that the dropped position reduced the drag by 7.8%, the time trial position reduced the drag by 12.4% and Obree's position reduced the drag by 27.8%, all referenced from the upright position. The drag reduction of Obree's position is highly significant.

The drag of a cyclist is reduced as the rider gets into a more aerodynamic position. Some cyclists find achieving aerodynamic stances easier than others, often due to differences in body size. Swain *et al.* (1987) examined the effect of body size on a rider's oxygen consumption. Swain explained that, because a larger cyclist has a greater surface area than a smaller cyclist, the larger cyclist has more absolute air resistance. However, the larger cyclist has a lower ratio of surface area to body weight and thus a lower relative air resistance for his or her muscle mass to overcome. It was hypothesised and found that large cyclists had a lower oxygen consumption to body weight ratio, 22% lower. This was due to the lower surface area to body weight ratio, and the corresponding frontal area to body weight ratio.

Wheels

The wheels make up a large and important proportion of the bike geometry, and are an influential factor on the airflow around the bike. Several studies have specifically focused on wheel aerodynamics both from an analysis and optimisation standpoint.

With the introduction of composite materials in the mid-eighties new wheels began to take shape. Kyle (1989b) carried out wind tunnel tests on different wheels with bicycle-component manufacturers HED. The tests revealed trends but no fine details between the wheels; this was due to the insensitivity of the force balance. The results showed that disc wheels and tri-spoke wheels had the lowest drag. A conventional wheel with an 18 mm tyre and a wheel with an aero rim with 18 bladed spokes were only slightly higher.

McCole *et al*. (1990) and Hagberg & McCole (1990) examined the effect that riding with different wheels might have on oxygen consumption. Eight sets of wheels were tested but only two stood out as being noticeably beneficial. An aerodynamic set of wheels with 16 front spokes and 18 rear reduced the oxygen consumption by 7 ± 5% and a set of disc wheels reduced the oxygen consumption by 3 ± 4%. It is supposed that this method of analysis does not have the sensitivity to recognise the subtle difference between many wheels; such components are possibly easier to analyse in a more controlled environment.

Kyle (1991a) presented a comprehensive analysis of 25 wheels carried out in a 0.6 by 0.9 m working section wind tunnel at the University of California in Irvine. The wheels were tested at 20 to 35 mile h^{-1} on a force balance accurate to ±0.05 N with a stationary wheel or ±0.1 N if the wheel was rotating. Five different groups of wheels were investigated:

1. seven lenticular disc wheels (a disc wheel that curves outward between the rim and hub)
2. five flat disc wheels
3. six 3- and 4-spoked aerodynamic composite wheels
4. five conventional aero wheels with steel bladed spokes and shallow aluminium aero rims
5. two newly developed aero wheels with steel bladed spokes and deep aluminium aero rims.

Tests on wheels of different sizes revealed that there wasn't much difference in drag between 24 in, 26 in, and 27 in wheels. With the wind parallel to the axis of the wheel the lenticular and flat disc wheel performed similarly. However, lenticular wheels perform more favourably in the presence of a crosswind, as the flat wheel will stall before the lenticular wheel. The drag on all 12 disc wheels tested was approximately 1 to 1.1 N at 30 mile h^{-1}. The best of the conventional spoked aero wheels had only 18 bladed spokes with an aluminium aero rim. The drag of these wheels was uniformly higher than that of the disc wheels, by 0.34 to 0.49 N at 30 mile h^{-1}. The best of the 3- and 4-spoked aerodynamic wheels had a drag that was comparable to the best disc wheels. However, some of them had 0.1 to 0.34 N higher drag than the discs. In general the greater the number the spokes the greater the drag; therefore of the spoked wheels the 3-spoked wheels had the lowest drag. Different tyre sizes were also investigated. This revealed that the rim should be no wider than the tyre. If the two remain the same width then the likelihood of separation was reduced and the drag was minimised. Of the deep-section aero rim wheels one had 18 spokes and the other had 12. The 12-spoked wheel was the most efficient and had a drag comparable to the discs and 3-spoked wheel. The 18-spoked wheel was more favourable than the standard aero wheels, but not as efficient as the discs.

Zdravkovich (1992) investigated wheel aerodynamics in a wind tunnel. The ratio of wheel diameter to tyre tube cross-sectional diameter, known as the shape factor, was found to have a large influence over the body axis drag on the wheel. Experiments using a narrower racing tyre, thus increasing the shape factor, increased the drag coefficient significantly. Zdravkovich supposed that the use of thin plates located behind bluff bodies, known as splitter plates, may reduce the drag. This hypothesis was based upon the findings of Apelt *et al.* (1975), who showed that a splitter plate of length 1.5 times the diameter of a circular cross section object will prevent the formation of a vortex street and reduce the pressure drag (Fig. 3). Splitter plates of 2*d* and 4*d* length, where *d* is the distance from the bottom of the rim to the top of the wheel, were woven between the spokes and attached to the rim of the wheel, resembling a modern deep section rim. Zdravkovich also constructed a disc wheel made from a standard bike wheel with sheets attached to the sides. The wind tunnel experiments showed that the 2*d* splitter plates resulted in a 5% axial drag reduction. In contrast the 4*d* splitter plates and the full disc actually increased axial drag on the wheels. The side forces on the wheels were also measured, and found to increase linearly with yaw angle. The 2*d* splitter plates were found to increase the side force by 3.5 times that of a standard wheel, and the disc wheel 11 times the side force of a standard wheel. Zdravkovich concluded that the vortex shedding around bicycle geometry was weak and therefore the splitter plates had little effect on the reduction of drag.

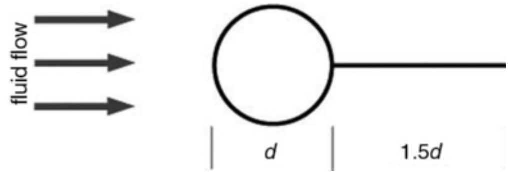

Figure 3 Splitter plates of length 1.5*d* located behind a cylindrical object of diameter *d*.

Capelli *et al.* (1993) attempted to determine whether a lenticular wheel outperforms a traditional disc wheel under the same conditions. In this study two cyclists were towed around a velodrome on four different bike configurations: an aerodynamic frame with lenticular wheels; an aerodynamic frame with traditional wheels; a traditional frame with aerodynamic wheels; and a traditional frame with traditional wheels. A load cell was used to measure the force on the towed cyclist, from which the traction resistance was determined. Complying with previous understanding the traction resistance was found to be proportional to the square of wind velocity. The study found that, in terms of mechanical energy saving, the role of lenticular wheels is negligible.

Greenwell *et al.* (1995) studied the body axis and side forces exerted on seven bicycle wheels in a full-scale wind tunnel. Six of the seven wheels tested (or today's versions of them) are shown in Fig. 4. Greenwell *et al.* used an experimental setup consisting of the rear of a frame and wheel suspended from a centre balance (Fig. 5). It was found that because of the tread of the tyre no significant laminar region occurred, and the flow transitioned to turbulent almost immediately, a characteristic that would be enhanced in real situations, due to debris on and around the tyre. For all but one the wheels the results were negligibly affected by the different rotating speeds, the one

Figure 4 The 'aerodynamic' wheels tested by Greenwell *et al.* (1995) (a) Campagnolo Shamal; (b) Specialized Ultralight; (c) HED disc; (d) HED CX (HED JET shown); (e) Fir Tri-spoke (Fir 3 Razze Carbon wheel shown); (f) Zipp 950 Disc

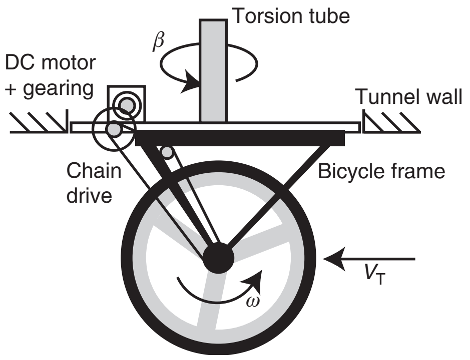

Figure 5 The experimental apparatus used by Greenwell *et al.* (1995)

exception being the disc wheel body axis force at very high yaw angles. It was found that at a zero yaw angle the spoked 'aerodynamic' wheels gave a 23% reduction in drag and the disc wheel a 26% reduction, compared to the drag on a standard wheel. All the 'aerodynamic' wheels were found to have similar drag levels at a zero yaw angle. As yaw angle increased, the body axis force on the spoked wheels increased, up to approximately 45°, followed by a decrease after 45°. The trispoke wheels showed an initial rapid fall in body axis force, followed by an increase, then a final reduction towards zero as yaw angle approached 90°. The disc wheels showed a very rapid reduction in body axis force, levelling off at around zero by 15°. These results showed that, for body axis force, the disc wheels clearly outperform all others. The side force imposed on the tri-spoke and spoked wheels was found to increase gradually with yaw. The magnitude of the side force was found to increase linearly with projected side area of the wheel. The disc wheels behaved almost like a wing, in that a distinctive stall was witnessed at a yaw angle of approximately 25°. The side force on the disc wheels at very high yaw angles was five times that of a standard wheel, and at very low yaw angles eight to ten times. The instability of disc wheels experienced in side winds by many riders was found to be due to the increased side force, and also the increased moment due to the aerodynamic drag force acting ahead of the steering axis.

Tew and Sayers (1999) studied the aerodynamic characteristics of six different bicycle wheels. The investigation was carried out on full-scale wheels in a wind tunnel at a range of yaw angles, between 0° and 30°. Body axis forces and side forces were resolved using the wind tunnel force balance, which measured lift and drag. The wheels investigated are shown in Fig. 6. The results showed that, of the six wheels, the Campagnolo Shamal, Mavic Cosmic, Spinergy and Specialised Trispoke wheels performed very similarly and these four wheels shall be collectively referred to as the 'intermediate wheels'. At 0° yaw angle the intermediate and disc wheels produced 60% and 70% less body axis drag than the standard wheel, respectively.

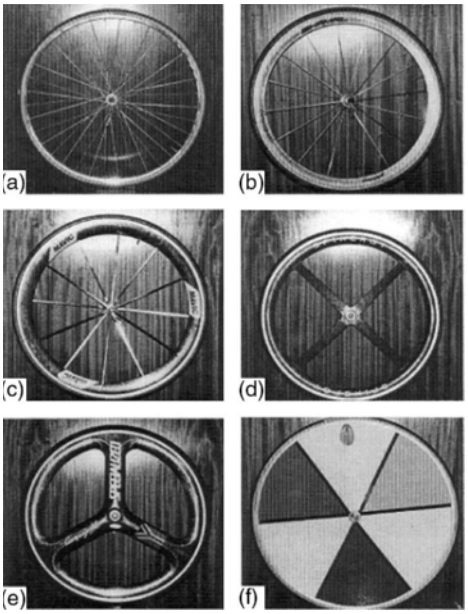

Figure 6 The investigated wheel designs:
(a) Standard 36 spoke wheel; (b) Campagnolo Shamal wheel; (c) Mavic Cosmic wheel; (d) Spinergy wheel; (e) Specialised Trispoke wheel; (f) Disc wheel (Tew and Sayers, 1999)

The body axis drag of a standard wheel increased with yaw angle, presumed due to the increased exposure of the spokes to the air stream. The intermediate wheels also experienced this increase in body axis drag but to a lesser extent. The body axis drag on the disc wheel was found to increase suddenly, although the angle at which this sudden increase occured decreased with wheel speed. For a given yaw angle of the disc wheel the body axis drag reduced rapidly with increasing speed. For the standard and intermediate wheels the side force component was independent of speed. The standard wheel had the lowest side force component whereas the disc had the highest. At 30 km h^{-1} the disc wheel had the lowest body axis drag at low yaw angles and the highest at high yaw angles. At higher speeds the body axis drag of the disc wheel decreased, and was as low as the intermediate wheels at a speed of 55 km h^{-1}. The results of the study confirmed the observations of many cyclists – that in calm conditions disc wheels appear advantageous, but in gusty conditions the discs are unstable and can hinder one's performance. The similarity of results for the intermediate group is also an interesting finding, since the difference in their price and claims of efficiency might have suggested otherwise.

Hanna (2002) claimed that there was little clear evidence to support the use of rear disc wheels in cycling, and aimed to quantify the speculation that the wheel acts as a sail. The study was performed using computational fluid dynamics (CFD). It was demonstrated that CFD has the advantage of being able to compute the skin friction and pressure drag independently, quantities that are not easy to measure independently. Simulations were carried out on a representative full bike and rider travelling at 25 mile h^{-1}, with a constant 90° crosswind imposed. Both spoked and disc rear wheel configurations were analysed, and the crosswind varied from 0 to 30 mile h^{-1}. The results demonstrated the increasing magnitude of drag experienced in a crosswind (Fig. 7). The simulations showed that, in still air, a rear disc wheel reduces drag by about 2%. In a 20 mile h^{-1} crosswind (39° yaw angle) the rear disc wheel reduced the drag over the standard wheel by 17%. However the disadvantage of the disc wheel was also outlined where in a 20 mile h^{-1} cross wind the side force acting on the bike and rider was doubled. Without any experimental validation these quantitative results should be approached with caution. However, they confirm once more the observations of many riders, that disc wheels will reduce drag, but in gusty side wind conditions they should be avoided because of the danger of large and sudden side forces.

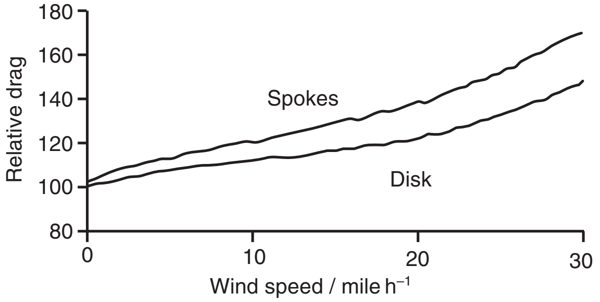

Figure 7 Graph of relative drag difference between a cyclist using a rear wheel with and without a disc, in a 0 to 30 mile h^{-1} crosswind Hanna (2002)

Bike design

McCole *et al.* (1990) and Hagberg & McCole (1990) extended their study to examine the impact of riding an aerodynamic bike and a standard bike while monitoring oxygen consumption. The aerodynamic bike included cow-horn handlebars, a sloping top-tube and a 24 in front wheel. When riding the aerodynamic bike the riders' oxygen consumption was 7 ± 4% lower than on the standard bicycle.

Kyle (1991b) presented an investigation into 20 different bikes tested with and without riders at the California Institute of Technology. Road bikes, time-trial bikes and pursuit bikes were all tested. It was found difficult to get repeatable measurements (± 0.44 N) due to slight changes in position for each test. With no rider the tests were repeatable to ± 0.13 N. As expected the pursuit bikes performed the best and the road bikes the worst. Of the road bikes the one that performed significantly better shielded exposed components, such as cables, brakes and water bottles by integrating them into the frame. Of the pursuit bikes the best performer (bike only) was an aero-composite bike by Dupont, which had half the drag of the worst bike, a Schwinn track bike with steel round tubes. Many of the bikes analysed in this paper are now illegal since the UCI redefined the rules in 2000.

Zdravkovich (1992) investigated the aerodynamics of a bicycle frame and the effect of attaching splitter plates (Fig. 3) to the frame tubes. It was found that having 2*d* splitter plates on a frame reduced the drag coefficient by approximately 4%. It was also found that the handlebars contributed to 10% of the drag on the frame and all components except wheels, saddle and seat-post. Interestingly, the results showed that the drag coefficient did not change with Reynolds number.

By measuring the traction resistance and also the energy cost of cycling per unit distance, Capelli *et al.* (1993) studied the aerodynamic benefit of riding a bicycle with an aerodynamically optimised frame. Measurements were recorded by towing two riders around a velodrome. It was found that a bike with an aerodynamic frame would travel approximately 3% faster than a bike with a traditional frame.

The aforementioned LotusSport bicycle was considered a leader in a time of great development for bicycle aerodynamics. Hill (1993) described the development of Chris Boardman's record breaking machine. The frame consisted of a single blade connecting the head tube to the seat tube and was analysed by comparing it to a traditional tubular diamond frame. The bikes were tested at the Motor Industry Research Association (MIRA) wind tunnel, of 35 m^2 working cross section. The bikes were tested at a typical 4000 m Olympic race speed of 14.5 ms^{-1}. Somewhat surprisingly the results showed that the drag on the Lotus bike, with a rider, was 6.6% higher than the conventional bike. However, when the bikes were compared with no rider, the Lotus bike had 30% less drag than the traditional bike. The position of the rider on the Lotus bike was then altered, so that it was closer to the traditional racing position. The results now showed that with the altered position a rider would take 2.2 seconds less to complete a 4000 m race on the Lotus bike (no indication is given in the publication regarding the magnitude of drag reduction). Special features of the Lotus bike were a 'nose' in front of the headset and a 'foot' in front of the bottom bracket, both designed to deflect the airflow around the awkward geometry. Once all the modifications had been made the Lotus bike was found to have 16% less drag than the traditional bike. It is worth noting that tests were carried out with a stationary rider as well as with a rider pedalling. The resulting variation was negligible, although the moving condition did not include rotating wheels.

The Lotus bike set a precedent for monoque frames both on the track and in road time trials. Shortly after the development of the Lotus bike, a project team from the Royal Melbourne Institute of Technology (RMIT) and the Australian Institute of Sport (AIS) set about developing their own world class bicycle (Thompson, 1998). The aerodynamic development of the 'Superbike' used unique wind tunnel techniques in an attempt to simulate accurately real cycling conditions. This involved using artificial Styrofoam legs attached to the pedals. The rear wheel was driven by an electric motor under the wind tunnel floor, and a simple drive belt drove the front wheel. This motor driven setup allowed highly repeatable conditions, and therefore also repeatable results (Fig. 8). The results of the wind tunnel experiments showed that the optimised Superbike required 5% less power than the previous steel tubular frame produced by AIS.

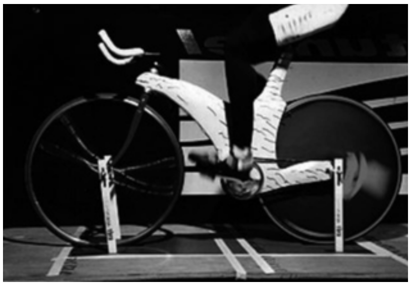

Figure 8 The aerodynamic analysis of the Australian Superbike

Drafting

The effect of drafting, i.e. one rider riding in the wake of another, is a highly noticeable factor to any cyclist who rides in a group. The observable effect of drafting is a reduction in the effort required to maintain a specific speed, and seemingly the lead rider creates an artificial tail wind. Several authors have attempted to quantify the effects of drafting.

Kyle (1979) studied these effects using coast down tests in a 200 m long hallway. The results showed that the leading rider was unaffected by a rider, or even riders, drafting in his wake. The trailing rider was found to benefit greatly from riding in another rider's wake by consuming 33% less power output than the lead at 40 km h^{-1}. This is an aerodynamic improvement of 38%, since the rolling resistance would be unaffected by drafting. Kyle found that in a group formation, or pace line, there is very little difference between being second in line or last, which is concurred by experienced riders. Kyle also found that the closer the trailing rider was to the lead, the more the drag on the trailing rider was reduced. With no gap there was a 47% drag reduction and with a 2 m gap there was a 27% drag reduction.

The work of McCole *et al.* (1990) and Hagberg & McCole (1990) studied the effect of drafting by monitoring the oxygen consumption of cyclists as they rode outdoors at speeds from 32 to 40 km h^{-1}. Analysis of 92 trials gave the following equation to estimate the oxygen consumption ($\dot{V}O_2$).

$$\dot{V}O_2 = -4.5 + 0.17\,\textit{riderspeed} + 0.052\,\textit{windspeed} + 0.022\,\textit{riderweight}$$

Drafting behind a single rider with a 0.2 to 0.5 m gap was found to reduce oxygen consumption by 18 ± 11% at 32 km h^{-1} and 27 ± 8% at 37 and 40 km h^{-1}. Drafting behind one, two and four riders resulted in the same oxygen consumption reduction at 40 km h^{-1} (27 ± 7%). Drafting in a group of eight (two riders at the front, three in second row, subject in third row with a rider either side) reduced the oxygen consumption by 39 ± 6%. Drafting behind a vehicle at 40 kmh^{-1} decreased the oxygen consumption by 62 ± 6%.

The effect of drafting was studied by Zdravkovich *et al.* (1996), with the drag on a trailing rider measured in 20 different positions. The results showed that a 49% drag reduction was experienced with the trailing rider directly behind the leader. However, this position was deemed too dangerous to be adopted in a racing situation. The next best position gave a drag reduction of 37%, where the trailing rider had a lateral offset of 10 cm. The findings also showed that the efficiency of the aerodynamic shielding reduces abruptly between a gap of 20 cm and 30 cm directly behind the lead rider.

Van Ingen Schenau (1988) quantified drafting by claiming that riders travelling in a group of two and a group of five will travel 5% and 10% faster than a lone rider, respectively.

Broker (2003) presented work carried out on the USA National Team as they prepared for the 1996 Olympic Games. Data was collected from three sources: wind-tunnel tests and power measuring cranks used in two different velodromes, one in the USA (outdoor) and one in Australia (indoor). Four cyclists were positioned in a pace line in the wind tunnel and rode in a pace line in the velodrome; force and power was measured for all four positions in the line. The power required to ride in all four positions in the pace line is shown in Fig. 9, expressed as a percentage of the lead power. The power required to ride in the second position in the pace line was approximately 61 to 66% of the lead power. In the third and fourth position the benefit was a 57 to 62% reduction in power requirement. It was also observed that the benefit of riding in a pace line was seemingly greater when studied in the wind tunnel. This was due to the highly controlled environment in the wind tunnel as opposed to the velodrome, where riders are free to move from side-to-side. Riding in a pace line appears to be least favourable when riding in an outdoor velodrome, e.g. in Atlanta, USA. This is, of course, due to a pace line offering little protection from sidewinds, which can be experienced on outdoor tracks.

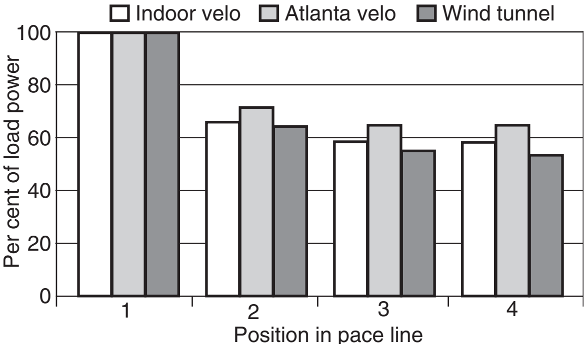

Figure 9 The effect of drafting on cycling power (Broker, 2003)

Choice of clothing

In an attempt to study the effect of the reduction of skin friction, Kyle & Burke (1984) investigated the effects of different clothing. An 11% reduction in drag was experienced when the rider swapped a standard Lycra Spandex skin suit for a full-length Lycra suit with an aero hood and mittens. It was proposed that this reduction was due to the covering up of arm and leg hair; however track and road riders do shave both leg and arm hair, so the reference value for this statistic appears flawed.

Pons & Vaughan (1989) stated that the reduction in aerodynamic drag brought about by changing from wearing trousers and a jacket to tight fitting clothing is 30%.

Kyle (1991b) reported on tests carried out in 1986 at the California Institute of Technology. Three Lycra suits, one wool jersey and one polypropylene warm-up suit were tested. The Lycra suits performed noticeably better, giving a 7.6 to 8.4% drag reduction over wool and a 9.8 to 10.5% drag reduction over polypropylene. Of the three Lycra suits the rubberised Lycra was slightly better than the standard Lycra.

Recently sports clothes manufacturers have been focusing on reducing aerodynamic drag when designing cycling skinsuits: all-in-one clothing used predominantly in time trialing and on the track. Companies such as Nike (Kyle & Brownlie, 2002) and Speedo have been specifically focusing on the positioning of seams and fabric roughness to dictate where the flow will and will not separate. Brownlie *et al.* (2004) sought to reduce the drag on a speed skater by having textured fabric that would trip the boundary layer to turbulent and reduce the wake downstream of the skater. This was achieved by having fabrics of varied roughness on different body parts, determined by the size and thus Reynolds number of each given body part. Kyle *et al.* (2004) led the development of the 'Nike Swift Spin' skinsuit, designed specifically for time trials. Wind-tunnel tests were carried out to compare prototype and commercial suits. From the results several methods were found to reduce the resistance. Custom fitted stretched fabric was used as it avoided loose fabric and wrinkles. The fabric texture was varied accordingly in different zones. In some segments rough fabric was chosen because it advanced transition, and in others smoother surfaces were chosen to reduce surface friction. Seams were aligned with the flow and kept to a minimum in regions where the flow was still attached. It was found that in limb segments with cross flow the fabric gave a lower drag than bare skin. Taking the above steps would give a drag reduction over a standard suit of 6% without pedalling and 4% when pedalling.

Helmets

Over the last 20 or so years manufacturers have produced helmets that seek to prevent the air flowing over a rider's head from separating and recirculating. This is achieved by having a helmet or aerohat that protrudes from the back of the head and fills the void between the head and the upper back. In 2002 the UCI changed its helmet regulations so that all helmets worn should now be safe. As a result there is now a new generation of helmets that are characteristically bigger, but follow the same principles of trying to achieve attached flow between the head and back.

Kyle & Burke (1984) found that there was a 7% drag reduction when the rider wore an aerohat.

In the previously mentioned work with HED, Kyle (1989b) tested an aerohat at the Texas A&M wind tunnel. The results showed that having an aerohat is preferable to having no helmet at all. The optimum angle of the head was found to be at 45°, as opposed to all the way back (looking directly ahead) or facing down to the road.

Two different aerohats were studied in a wind tunnel by Chin & Lim (2001). Both helmets performed similarly and were compared to wearing no helmet in four different positions. The head and helmet were positioned at three different angles to the ground (30°, 45° and 60°) and also with the head facing sideways. The only position that improved the aerodynamics of the rider was at 45°; the other three stances were detrimental to aerodynamics.

The effect of wind

Headwinds and tailwinds were found to reduce or increase the rider's speed by approximately 60% of the speed of the wind, according to Kyle & Burke (1984). Crosswinds were shown to increase the drag on the rider, the extent of which depended on the yaw angle.

Kyle (1990) found that it is more beneficial to cycle uphill with a tailwind and downhill with a headwind than uphill with a headwind and downhill with a tailwind.

The performances of bikes at different angles into the oncoming wind, or yaw angles were examined by Hill (1993). It is understood that for conventional bikes the drag rises as the yaw angle increases up to approximately 10°, and then gradually decreases again. This was not the case for the LotusSport monocoque bike: as the yaw angle increased from zero the drag did not rise; in fact it steadily decreased, and at all angles remained less than the drag on the traditional bike (Fig. 10). This interesting result was due to the aerodynamic sail effect created by the slender blade of the monocoque frame. The effect of a velodrome crosswind was investigated using a computational iterative process. The results showed that the traditional bike, as expected, loses a lot of time when subject to a cross wind. However, due to the sail effect, the monocoque bike actually gains time under crosswind conditions.

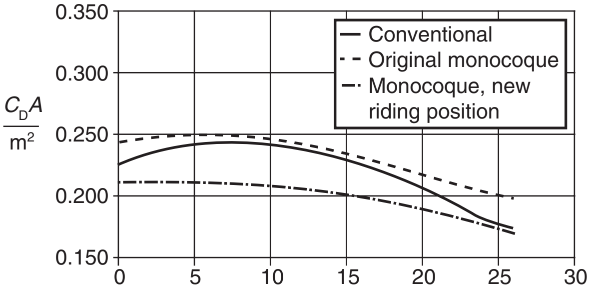

Figure 10 The effect of yaw angle (Hill, 1993)

Mountain biking

The aerodynamics of mountain biking have been investigated far less than in track or road racing. The reasons for this are apparent when considering the additional losses and far lower average speeds in this discipline.

Sunter & Sayers (2002) investigated the advantages of attaching a fairing to the front wheel of a downhill mountain bike (Fig. 11). With a 10 mm displacement between wheel and deflector the drag reduction was 10%. This reduction in drag was found to decrease as the deflector moves away from the wheel. At a speed of 15.5 m s^{-1} the drag force reduction of using the deflector was 0.78 N. The total aerodynamic force on a mountain bike was quoted as 36 N, giving a drag reduction due to the deflector of 2.17%. It was also approximated that the rolling resistance of the tyres was 10 N, giving an overall resistance of 46 N, and a percentage decrease for the downhill rider with a deflector of 1.7%.

Figure 11 A deflector attached to a mountain bike (Sunter & Sayers, 2002)

Lukes *et al*. (2004) used CFD to study the flow around a mountain bike and rider. The investigation showed that as far as aerodynamic drag is concerned, the rider contributes 64%, the forks 7% and the handlebar, front wheel and frame all individually contribute approximately 6.5%. An analysis of different forces at different speeds revealed that the aerodynamic force only became more dominant than rolling resistance at speeds above 8.75 m s^{-1}. This compares interestingly with road cycling because at this speed on a road bike over 90% of the resistance is attributed to aerodynamics (Kyle and Burke, 1984). This study importantly illustrates the role that CFD can play in analysing the aerodynamic characteristics of bicycles. The study is presented with explanations of the computational methods used, which the reader may find builds a broader understanding of CFD analysis.

Summary of drag reduction findings

The quantitive findings presented in the reviewed studies are summarised in Tables 1 to 6. A table similar to these is presented by Broker (2003) showing the advantages and disadvantages of various smaller bicycle components.

Shortfalls in literature

Many authors have examined and quantified various aspects of cycling aerodynamics. There do however remain some gaps in the understanding. Simplifications in testing are common, often due to the limited accessibility of research tools. For example, components such as wheels, frames and forks

Table 1 A summary of the general bicycle aerodynamics findings

	Nonweiler (1956)	Pugh (1974)	Prampero di *et al.* (1979)	Davies (1980)	Kyle & Burke (1984)	Hill (1993)	Kyle (2003)	Lukes *et al.* (2004) [mountain bike]
Drag coefficient	0.93	0.79	$0.38/A\rho$	0.56			0.8–0.9	
Contribution of aerodynamics to total drag					50% (3.6 ms^{-1}) 90% (8.9 ms^{-1})	96% (at race speeds)		50% (8.75 ms^{-1})
Contribution of aerodynamic drag by bike					31%–39%			36%

Table 2 The drag reduction of various positions, from the reference upright position

	Kyle & Burke (1984)	Kyle (1991b)	Grappe *et al.* (1997)
'Ski jump' position – hands behind seat		12%	
Dropped position	20%		7.8%
Time trial position			12.4%
Hill descent position	28%		
Obree's position			27.8%

Table 3 Aerodynamic influence of various wheels

	McCole *et al.* (1990)	Kyle (1991a)	Zdravkovich (1992)	Capelli *et al.* (1993)	Greenwell *et al.* (1995)	Tew & Sayers (1999)	Hanna (2002)
Body axis drag reduction from standard wheel at 0° yaw							
1.4 times tyre thickness			75%				
With 2d splitter plate			5%				
With 4d splitter plate			Increase				
Disc wheel			Increase		26%	70%	2%
Aerodynamic wheels					23%	60%	
Difference between lenticular and flat wheel				0			
Drag force (N)							
Disc wheel		1–1.1					
3 and 4 spoked aerodynamic wheels		1–1.44					
18 bladed spokes on shallow aero rim		1.34–1.59					
Oxygen consumption reduction							
Aerodynamic wheel set – 16 front and 18 rear spokes	7±5%						
Disc wheels	3±4%						

Table 4 Aerodynamic influence of various frames compared to standard frames

	McCole *et al.* (1990)	Zdravkovich (1992)	Hill (1993)	Capelli *et al.* (1993)
Drag reduction				
Standard frame with 2d splitter plates		4%		
Monocoque frame with rider			16%	
Monocoque frame without rider			30%	
Velocity increase				
Aerodynamic frame				3%
Oxygen consumption reduction				
Aerodynamic frame	7 ± 4%			

Table 5 Aerodynamic drag reduction of various equipment

	Kyle & Burke (1984)	Pons & Vaughan (1989)	Kyle (1991b)	Zdravkovich (1992)	Kyle *et al.* (2004)
Wearing a Lycra suit	11%				
Wearing an aerohat	7%				
Handlebar contribution to drag				10%	
Exchanging trousers and jacket for tight fitting clothing		30%			
Exchanging wool suit for Lycra suit			7.6-8.4%		
Exchanging polypropylene suit for Lycra suit			9.8-10.5%		
Exchanging a standard suit for Nike Swift Spin skinsuit (pedalling)					4%
Exchanging a standard suit for Nike Swift Spin skinsuit (not pedalling)					6%

Table 6 Aerodynamic influence of drafting

	Kyle (1979)	McCole *et al.* (1990)	Zdravkovich *et al.* (1996)	Brooker (2003)
Drag reduction				
No offset	47%		49%	
10 cm offset			37%	
30 cm wheel gap	38%			
2 m wheel gap	27%			
Oxygen consumption reduction at 0.2 to 0.5 m gap				
Behind one rider at 32 km h^{-1}		18 ± 11%		
Behind one rider at 37 to 40 km h^{-1}		27 ± 8%		
Behind one, two and four riders at 40 km h^{-1}		27 ± %		
Surrounded by 7 other riders		39 ± 6%		
Behind a vehicle at 40 km h^{-1}		62 ± 6%		
Reduction of power required to maintain a given speed				
Second in the pace line				61–66%
Third or fourth in pace line				57–62%

may be tested individually where it is assumed that the interaction of the flow between the missing components will not affect the qualitative result. However, it may well be the case that the interaction between a number of components will adversely affect the flow in ways only apparent when the system is examined as a whole.

A continuation of the flow interaction issue is the consideration of the unsteady flow caused by the movement of the rider. A small number of the previous studies (Hill, 1993; Thompson, 1998; Kyle *et al*., 2004) have made passing comments about the differences between stationary and moving legs, but there not yet any quantitive data on the foreseeable differences between these conditions. The relevance of this lack of understanding becomes apparent when considering that a bicycle may display different aerodynamic characteristics under the two alterative conditions.

Future research

With the Union Cycliste Internationale (UCI) enforcing tight restrictions on bicycle development, reducing aerodynamic drag is more of a challenge than ever. However, as technologies develop and powerful research tools become more accessible, bicycles will continue to advance. Future research will not only seek to fill gaps in the current understanding but also assist the analysis and development of future designs. This understanding may develop dramatically if the flow around the entire bike and rider, as a whole, is examined, understood and quantified. It is also deemed a logical and necessary future step to examine the dynamic aspects of elite cycling and assess their influence on aerodynamic drag. Included in the ‘dynamic’ category should be movement in the head and upper body, which can be particularly apparent when riders are fatigued.

Computational advances now allow fluid dynamics conundrums to be solved using CFD (Hanna, 2002; Lukes *et al*., 2004). This tool will allow researchers to concur with and advance upon previous and future wind tunnel tests. CFD will provide the researcher with the ability to compute many output forces and identify the exact components which cause the most drag, a result which is extremely hard to achieve in wind tunnel testing. This will build a comprehensive understanding of the flow physics around the bike, which can only be to the good of future bicycle design and development. It will however be a number of years before CFD can be used to solve accurately flow around complex moving geometries, such as a pedalling rider. Wind tunnel, track and road testing will still have a large and important role in future analysis and will always provide data for validating CFD models. With this allegiance between wind tunnel testing and CFD the future looks exciting for bicycle aerodynamics research and development.

References

Apelt, C.J., West, G.A. & Szewczyk, A. A. (1975) The effects of wake splitter plates on, and the flow past, a circular cylinder in the range 104=Re=5104. Part 1. *Journal of Fluid Mechanics*, **61**, 187–198.

Ashley, S. (1993) Cheetah sprints to world record. *American Society of Mechanical Engineers*, 56–59.

Bassett, D.R.J., Kyle, C.R., Passfield, L., Broker, J.P. & Burke, E.R. (1999) Comparing cycling world hour records, 1967–1996: modeling with empirical data. *Medicine & Science in Sports & Exercise*, **31** (11), 1665–1676.

Broker, J.P. (2003) Cycling power: Road and mountain. In: *High-Tech Cycling: The Science of Riding Faster* (ed. Burke, E. R.) Human Kinetics, Colorado, pp. 147–174.

Brownlie, L.W., Kyle, C.R., Harber, E., MacDonald, R. & Shorten, M.R. (2004) Reducing the aerodynamic drag of sports apparel: Development of the Nike Swift sprint running and SwiftSkin speed skating suits In: *5th International Conference on the Engineering of Sport*, Vol. 1 (eds. Hubbard, M., Mehta, R. D. & Pallis, J. M.) U.C. Davis, USA, pp. 91–96.

Capelli, C., Rosa, G., Butti, F., Ferretti, G., Veicsteinas, A. & di Prampero, P. (1993) Energy cost and efficiency of riding aerodynamic bicycles. *European Journal of Applied Physiology*, **67** (1), 144–149.

Chin, K.Y. & Lim, L.K. (2001) *The design of aerodynamically sound, bike’s helmet*. Department of Mechanical Engineering, University of Adelaide, Adelaide.

Davies, C.T.M. (1980) Effect of air resistance on the metabolic cost and performance of cycling. *European Journal of Applied Physiology & Occupational Physiology*, **45** (1), 245–254.

Grappe, F., Candau, R., Belli, A. & Rouillon, J.D. (1997) Aerodynamic drag in field cycling with special reference to the Obree’s position. *Ergonomics*, **40** (12), 1299–1311.

Greenwell, D.I., Wood, N.J., Bridge, E.K. L. & Addy, R.J. (1995) Aerodynamic characteristics of low-drag bicycle wheels. *Aeronautical Journal*, **99** (983), 109–120.

Gross, A.C., Kyle, C.R. & Malewicki, D.J. (1983) Aerodynamics of Human-Powered Land Vehicles. *Scientific American*, **249** (6), 126–134.

Hagberg, J.M. & McCole, S.D. (1990) The effect of drafting and aerodynamic equipment on the energy expenditure during cycling. *Cycling Science*, **2** (3), 19–22.

Hanna, K.R. (2002) Can CFD make a performance difference in sport? In: *4th International Conference on the Engineering of Sport* (eds. Ujihashi, S. & Haake, S.J.) Blackwell Science, Kyoto, Japan, pp. 17–30.

Hill, R.D. (1993) Design and development of the LotusSport pursuit bicycle. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, **207** (4), 285–294.

Johnson, S.C. & Schultz, B.B. (1990) The physiological effects of aerodynamics handlebars. *Cycling Science*, 29–12.

Kim, I. (1990) Racers, rough riders, and recumbents. *Mechanical Engineering*, **112** (5), 52–59.

Kyle, C.R. (1979) Reduction of wind resistance and power output of racing cyclists and runners travelling in groups. *Ergonomics*, **22** (4), 387–397.

Kyle, C.R. (1989a) The aerodynamics of handlebars and helmets. *Cycling Science*, **1** (1).

Kyle, C.R. (1989b) The aerodynamics of helmets and handlebars. *Cycling Science* **1**, 122–25.

Kyle, C.R. (1990) Chain friction, windy hills and other quick calculations. *Cycling Science*, **2** (3), 23–26.

Kyle, C.R. (1991a) New aero wheel tests. *Cycling Science*, **3** (1), 27–30.

Kyle, C.R. (1991b) Wind tunnel tests of aero bicycles. *Cycling Science*, **3** (1), 57–61.

Kyle, C.R. (2003) Selecting cycling equipment. In: *High-Tech Cycling: The Science of Riding Faster* (ed. Burke, E.R.) Human Kinetics, Colorado, pp. 1–48.

Kyle, C.R. & Brownlie, L. (2002) http://www.nike.com/nikecycling/index_flash.html.

Kyle, C.R., Brownlie, L.W., Harber, E., MacDonald, R. & Nordstrom, M. (2004) The Nike Swift Spin cycling project: Reducing the aerodynamic drag of bicycle racing clothing by using zoned fabric. In: *5th International Conference on the Engineering of Sport*, Vol. 1 (Eds, Hubbard, M., Mehta, R.D. & Pallis, J.M.) UC Davis, USA, pp. 118–124.

Kyle, C.R. & Burke, E.R. (1984) Improving the racing bicycle. *Mechanical Engineering*, **106** (9), 34–35.

Lukes, R.A., Hart, J.H., Chin, S.B. & Haake, S.J. (2004) The aerodynamics of mountain bicycles: The role of computational fluid dynamics. In: *5th International Conference on the Engineering of Sport*, Vol. 1 (Eds, Hubbard, M., Mehta, R. D. & Pallis, J. M.) U.C. Davis, U.S.A., pp. 104–110.

McCole, S.D., Claney, K., Conte, J.C., Anderson, R. & Hagberg, J.M. (1990) Energy expenditure during bicycling. *Journal of Applied Physiology*, **68** (2), 748–753.

Melton, M. (1990) The Huffy composite triton. *Cycling Science*, **2** (3), 8–12.

Nonweiler, T. (1956) *The air resistance of racing cyclists* Cranfield College of Aeronautics, Cranfield.

Nonweiler, T. (1958) The work production of man; studies on racing cyclists. *Journal of Physiology*, **141** (1), pp. 8–9.

Pons, D.J. & Vaughan, C.L. (1989) Mechanics of cycling. In: *Biomechanics of Sport* (ed. Vaughan, C.L.) CRC Press, pp. 289–315.

Prampero di, P.E., Cortili, G., Mognoni, P. & Saibene, F. (1979) Equation of motion of a cyclist. *Journal of Applied Physiology*, **47** (1), 201–206.

Pugh, L.G.C.E. (1974) The relation of oxygen intake and speed in competition cycling and comparative observations on the bicycle ergometer. *Journal of Physiology*, **241** (1), 795–808.

Richardson, R.S. & Johnson, S.C. (1994) Effect of aerodynamic handlebars on oxygen consumption while cycling at a constant speed. *Ergonomics*, **37** (5), 859–863.

Sunter, R.J. & Sayers, A.T. (2002) Aerodynamics of mountain bike tyres. In: *4th International Conference of the Engineering of Sport* (eds. Ujihashi, S. & Haake, S.J.) Blackwell Science, Kyoto, Japan, pp. 63–73.

Swain, D.P., Coast, J.R., Clifford, P.S., Milliken, M.C. & Stray-Gundersen, J. (1987) Influence of body size and oxygen consumption during bicycling. *Journal of Applied Physiology*, **62** (2), 668–672.

Tew, G.S. & Sayers, A.T. (1999) Aerodynamics of yawed racing cycle wheels. *Journal of Wind Engineering & Industrial Aerodynamics*, **82** (1), 209–222.

Thompson, L. (1998) Engineering the world's fastest bicycle. In: *2nd International Conference on the Engineering of Sport* (ed. Haake, S.J.) Blackwell Science, Sheffield, UK, pp. 99–109.

van Ingen Schenau, G.J. (1988) Cycle power: a predictive model. *Endeavour*, **12** (1), 44–47.

Whitt, F.R. & Wilson, D.G. (1982) *Bicycling Science*, The Massachusetts Institute of Technology.

Zdravkovich, M.M. (1992) Aerodynamics of bicycle wheel and frame. *Journal of Wind Engineering & Industrial Aerodynamics*, **40** (1), 55–70.

Zdravkovich, M.M., Ashcroft, M.W., Chisholm, S.J. & Hicks, N. (1996) Effect of cyclist's posture and vacinity of another cyclist on aerodynamic drag. In: *1st International Conference on the Engineering of Sport* (ed. Haake, S.J.) A.A. Balkema, Sheffield, UK, pp. 21–28.