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The effect of spatial position on the aerodynamic interactions between cyclists

Nathan Barry[a*], John Sheridan[a], David Burton[a], Nicholas A.T. Brown[b]

[a]*Monash University, Clayton, Melbourne, VIC, 3800, Australia*
[b]*Australian Institute of Sport, Belconnen, Canberra, ACT, 2617, Australia*

Abstract

Aerodynamic drag contributes the majority of the resistance acting on elite cyclists. At speeds of 50km/h, over 90% of an athlete's power output is expended overcoming drag. As a result, reducing the drag of cyclists significantly improves their performance. To date research on cycling aerodynamics has primarily focused on a single rider, despite the fact that many cycling events are mass start or team based, which necessarily involve athletes travelling in close proximity. Fundamental investigations of multiple less complex bluff bodies have shown strong aerodynamic interactions that significantly affect the forces they experience. Whilst practical experience has shown this to also be true for cycling, such effects are not well understood.

This paper reports the results of wind tunnel experiments that measured the variation in aerodynamic drag for cyclists in various two rider formations. Both drafting and overtaking formations were investigated; being inline parallel and perpendicular to the flow respectively. Loads experienced by both riders were mapped as a function of their relative spatial position. Results show that drag and side force are strong functions of spatial position. For two riders drafting directly inline there was a maximum drag reduction of 49% for the trailing rider and over 5% for the lead rider. During overtaking a drag increase of over 6% was recorded with riders positioned side-by-side.

Selection and peer-review under responsibility of the Centre for Sports Engineering Research, Sheffield Hallam University

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* Corresponding author. Tel +61 3 9905 5357
nathan.barry@monash.edu

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Nomenclature

C_DA	Drag coefficient Area – drag force normalised by dynamic pressure
C_SA	Side force coefficient area – side force normalised by dynamic pressure
$q = ½\rho V^2$	Dynamic Pressure
ρ	Freestream air density
V	Freestream air velocity – equivalent to rider velocity

1. Introduction

During elite competition over 90% of an elite cyclists power output is expended overcoming aerodynamic drag (Kyle & Burke 1984, Grappe 1997, Kyle & Weaver 2004). Therefore, optimising the aerodynamics of a cyclist has the potential to significantly improve performance. Over the past three decades significant advances have been made in improving cycling aerodynamics; both by modifying rider position and through better equipment design. However, to date research has focussed primarily on individual time trial performance, despite the fact that most road events and many track events involve riders travelling in close proximity. There remains limited understanding of the influence that the presence of additional riders can have on the performance of an athlete.

Coast down tests on multiple cyclists by Kyle (1979) investigated the effect of separation distance on aerodynamic drag reduction for drafting cyclists. A maximum saving of 35% was observed for trailing riders at minimum practical spacing with the benefit decreasing with separation distance. Broker et al. (1999) conducted a series of track tests with power measurement of pursuit teams. They found that the power required by a trailing rider was reduced by over 30% compared to the lead rider. This was attributed to reduced drag. Only a single spatial position was tested, which was the standard formation used by the team. For elite pursuit riders this gap is typically of the order of 100-200mm. Zdravkovich (1996) conducted wind tunnel tests of two full scale cyclists in a small closed section tunnel with varied separation distance, including lateral displacement from the centreline. Drag was measured for each athlete in a trailing position. A maximum drag reduction of 41-48% was found, with significant differences being observed in the drag of the two athletes. This showed that the reduction in drag will reduce with separation distance. However, for both riders the drag reduction decayed much more rapidly than found in the coast down results of Kyle. Computational simulations by Blocken et al. (2011) resulted in a lower drag saving of only 16% for a time trial riding position. However, the gradient of the drag curve was much lower than the results of Zdravkovich and more similar to the work of Kyle and other bluff body literature. This study also showed that there may be a benefit for the lead rider in a drafting pair; through reduced drag.

Crouch et al. (2012) showed that the wake of a cyclist has large separated regions and complex vortex topology, similar to other 3-dimensional bluff bodies. Thus, bluff body investigations may provide clues to better understanding the interaction effects between cyclists riding in close proximity. Fundamental research of circular cylinders arranged in line with the flow showed that there was a drag reduction for both the lead and trailing bodies, with the trailing body's reduction being far greater (Biermann & Herrnstein 1933, Hori 1959, Zdravkovich 1977). Drag on two cylinders arranged in line perpendicular to the flow increased significantly above the single body value when the two are in close proximity (Biermann & Herrnstein 1933, Zdravkovich 1977).

Given the complex and three-dimensional flow over a cyclist a more closely related scenario is that of ground vehicle interactions. A detailed study by Romberg et al. (1971) investigated overtaking and drafting positions of scale stock car models. Drafting tests observed a 37% drag reduction for the trailing vehicle inline at minimum separation and up to 30% saving for the lead vehicle at zero separation. Further tests were conducted for an overtaking manoeuvre which revealed a drag increase of 37% over the single vehicle value when the two vehicles were side-by-side, one slightly lagging the other.

Clearly, our current understanding of the influence of rider interactions on the aerodynamic loads of cyclists in close proximity is limited. Existing studies show a strong relationship between drag and position of riders.

However, there is no consistent trend for drag as a function of separation distance and forward interference for the lead rider is not clearly understood. In addition, the behaviour of aerodynamic forces when travelling side-by-side or during overtaking remains unknown as does the behaviour of forces other than drag. This study shows how aerodynamic forces acting on cyclists vary with relative spatial positions for two rider formations. This provides better insight into the drag changes that occur as a result of other rider interference, providing coaches with new information to modify tactics for team events.

2. Methodology

The investigation was divided into two separate studies of drafting and overtaking positions. All testing was conducted in the Monash University Wind Tunnel. This facility has a three-quarter open jet test section with a nozzle exit of 2.6m by 4m and a test section length of 11m. All tests were conducted at a wind speed of 65km/h which is the approximate steady state speed of a track pursuit team on a velodrome. This corresponds to a Reynolds number of $7\text{x}10^5$ using the cyclist torso chord as the characteristic length. A raised ground plane was required to house bicycle mounting and load cell apparatus. Testing used one athlete subject and a static anthropomorphic cycling mannequin. In both sets of tests only one of the two cyclists was instrumented. The other acted as interference only. Loads were measured using a set of four piezoelectric 3-axis load cells. This setup allows the resolution of full six axis forces and moments. The setup is shown in Figure 1. For drafting tests the static mannequin was used as the instrumented test subject for all runs. The benefits from the repeatable body position of the mannequin were determined to be an accepted trade off against the lack of pedaling dynamics. Trailing rider drag was measured by positioning the athlete ahead of the mannequin. The reverse setup was used to measure lead rider drag. The legs of the mannequin were set with thighs level as this generates the most symmetric wake (Crouch et al. 2012) and assumed to give the best representation of time averaged wake of a dynamic athlete.

Overtaking tests used the same basic procedure but a dynamic rider was used as the primary test subject with the mannequin acting as interference. The mannequin was positioned at the same static leg position with thighs level. A minimum lateral separation distance of 500mm exists between the two riders' centerlines, as this is the minimum practical distance achievable during competition. Different athletes were used for the drafting and overtaking experiments. It is noted that there is a noticeable size difference between the two test subjects (see Figure 1). The grid of spatial positions for the drafting and overtaking tests is described in Figure 2 below.

Fig. 1 (a) Drafting setup for trailing rider measurements– minimum separation shown; (b) Overtaking test setup at minimum separation

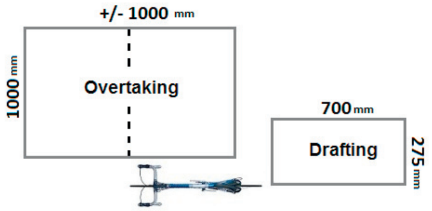

Fig. 2 – Spatial grid of drafting and overtaking positions

3. Results

3.1 Drafting

The drag of a cyclist was seen to vary significantly as a function of the proximity and location of a second rider (see Figure 3 below). This is consistent with the existing literature for other bluff body interactions. Force results show that drag is the only significant load acting on drafting riders under zero yaw conditions. Other axial forces and moments are all negligible. In addition to the expected reduction in drag for the trailing rider, the drag of the lead rider also decreased. This has not been previously observed experimentally, having previously only been observed in simulations by Blocken et al. (2011). The maximum reduction was 5% and 49% for the lead and trailing riders respectively. For both cases this occurred at minimum spacing with riders aligned axially.

The drafting benefit for the lead rider strongly depends on the axial distance while lateral displacement has a minor influence. The reverse is seen for the trailing rider with drag being a stronger function of the lateral displacement from the centreline than the axial separation distance. The limit of interactions was not reached for either rider as both still experienced a drag reduction at the edge of the test range. In the case of the trailing rider, at 700mm the drag saving over single rider formation is still over 40% for no lateral displacement. For the lead rider case, the measured saving at 700mm is only 2.5% but this is still greater than the uncertainty margin. Lead rider force measurements had an average uncertainty of less than 0.5% and less than 1% for the trailing rider.
The magnitude of drag saving for inline cyclists at close proximity seen in this study is comparable to the work of Zdravkovich (1996) but is greater than track test results by Broker et al. (1999) and Kyle (1979). This may be due to the difficulty in controlling and maintaining constant spacing during track tests which leads to less repeatable data. Track tests do not offer the same control over spatial position as wind tunnel tests and so it is expected that track tests will under predict the actual drag reduction due to fluctuations in relative position of the riders.

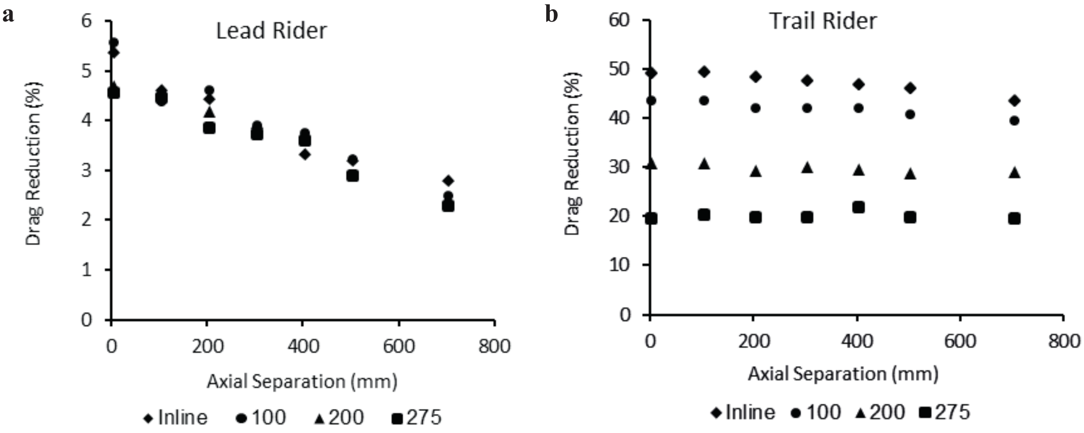

Fig. 3 (a) Percentage drag reduction for the leading rider; (b) Percentage drag reduction for the trailing rider.
Each series represents displacement in the lateral direction away from the centreline (mm)

The computational simulation by Blocken et al. (2011) seems to greatly under predict the magnitude of the drafting benefit compared to experimental work. However, the gradient of the present results is far more similar to the simulation results of Blocken et al. as well as Kyle's coast down work. The results of Zdravkovich degrade more rapidly with streamwise distance than other results in the literature. This is backed up by empirical results that suggest a drag saving is still present beyond the range indicated in the results of Zdravkovich.

It is noted that the difference in rider size is likely to influence the magnitude of interactions. The larger rider is likely to have greater impact on the smaller rider. As such, the change in drag seen here may represent an optimistic case as the instrumented subject was the smaller of the pair. This effect may be the cause of the two very different sets of drag results obtained by Zdravkovich as the subjects were two differently sized athletes. Differences in athlete size will occur through natural diversity and will be experienced in real world cycling.

3.2 Overtaking

During an overtaking manoeuvre there is a complex load interaction between the two cyclists. Unlike drafting, drag is not the only significant load; side force, roll moment and yaw moment all vary as a function of the relative spatial position. These loads are, however, lower in magnitude than the drag.

When referencing to a rider positioned on the left who is being overtaken on the right; the scenario for drag can be described as follows. The passing rider begins downstream, effectively sitting in a drafting position and there is a corresponding drag reduction for the primary (lead) rider. As the passing rider moves forward the primary rider's drag increases. At the point of being side-by-side both riders experience drag above the standalone value. As the passing rider continues forward the riders' drag begins to decrease. As the riders begin to conform to a drafting formation the drag again drops below the standalone value. This applies to the minimum practical lateral separation between riders of 500mm. As lateral distance is increased between the two riders the influence of the second rider is reduced and at 1500mm separation the interference is negligible. This can be seen in Figure 4a (below). Although interference appears to be negligible beyond 1500mm lateral separation, the limit in axial positions was not reached.

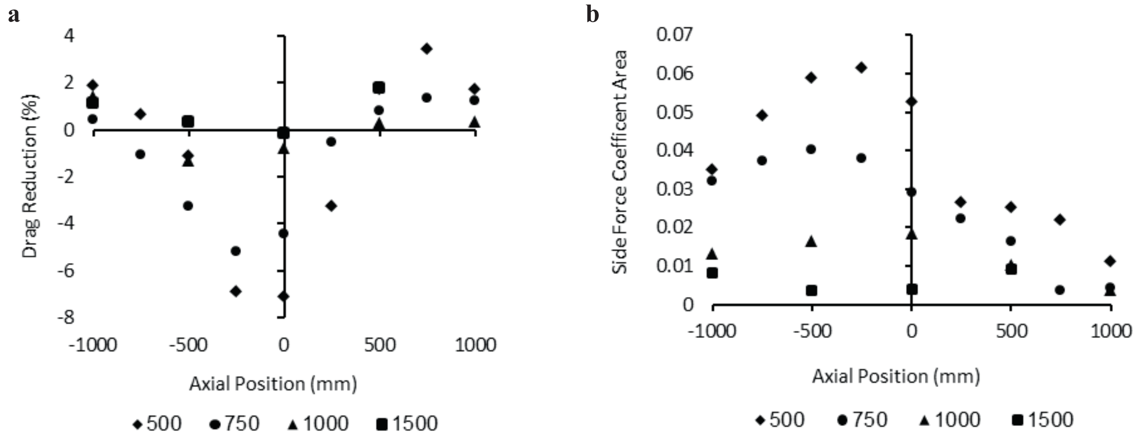

Fig. 4 (a) Percentage drag reduction for overtaking manoeuvre. Negative value indicates drag increase above solo rider value; (b) Side force coefficient area. Note that side force is negligible for a single rider. Series indicate lateral distance between rider centrelines (mm).

A standalone rider, or one in a drafting formation experiences negligible side force and moments at zero yaw conditions. However, during an overtaking manoeuvre the side force as well as roll and yaw moments become significant due to the interference of the passing rider. The side force varies as a strong function of axial and lateral position of the interfering rider, similar to drag. It can be seen in Figure 4b that the side force coefficient behaves similarly to drag, with a peak for the rider being passed occurring with the overtaking rider slightly downstream of the side-by-side position. Side force peaks at a maximum value that is approximately 25% of the drag force when the two riders are side-by-side and reduces with axial and lateral displacement. At the maximum test separation of

1500mm the side force was negligible. The side force is measured as positive for the rider on the left, which equates to a repulsive force between the two riders. This trend confirms behaviour similar to the vehicle work of Romberg et al. and the results seen on other bluff bodies (Biermann & Herrnstein 1933, Zdravkovich 1977). Roll and yaw moments followed a similar curve to the drag and side force. Peak values were observed close to the side-by-side formation at minimal axial separation and also decreased with both axial and lateral displacement.

4. Conclusion

This study investigated how aerodynamic loads on cyclists vary when they travel in a two-rider formation. A range of positions were tested to simulate drafting and overtaking manoeuvres. The aerodynamic loads, in particular drag, are strongly influenced by flow interference from the presence of a second rider. This behaviour is consistent with literature for other bluff bodies. Cyclists in a drafting pair will both benefit from reduced drag. The maximum savings found here were 5% and 49% reduction in drag for the lead and trailing riders respectively; occurring inline at minimum separation. As lateral and axial displacement is increased the benefit decreases. Other loads are negligible. During an overtaking manoeuvre the drag of the both cyclists increased by over 6% above the standalone value when travelling side-by-side at small separation. This effect reduces with increasing lateral distance between riders. During overtaking, side force, roll moment and yaw moment all become significant and have a similar functional relationship with position, with a maximum occurring when riders are positioned side-by-side and at minimum separation. It is noted that difference in athlete size is likely to influence interaction effects.

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