

9th Conference of the International Sports Engineering Association (ISEA)

Effect of crosswinds and wheel selection on the aerodynamic behavior of a cyclist

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Accepted 02 March 2012

Abstract

This paper reports aerodynamic testing results of various styles of bicycle wheels across yaw angles of 0 to 30 degrees. Wheels considered include disc wheels, a bladed spoke wheel and various depth dished wheels. Testing has been completed in a three quarter open jet test section wind tunnel with an anthropomorphic mannequin and rotating front and rear wheels. Data is provided as to the influence of the wheel type on the overall drag and side force, and yaw and roll moment of the rider and bicycle combination. The results demonstrate that the wheel type has a significant effect on both the aerodynamic drag and stability of the bicycle system, and that evaluation of wheel aerodynamic performance should not be based on drag alone.

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Keywords: Bicycle; wheel; yaw; drag; moments; aerodynamics; cross wind; performance

Nomenclature

C_{DA}	Drag area coefficient - Axial drag force normalised by freestream dynamic pressure
C_{SA}	Side force area coefficient – side force normalised by freestream dynamic pressure
CM_{XA}	Roll moment normalised by freestream dynamic pressure and bicycle wheelbase
CM_{ZA}	Yaw moment normalised by freestream dynamic pressure and bicycle wheelbase

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1. Bicycle Wheel Aerodynamics

The application of aerodynamic research to the sport of cycling has been occurring for several decades with significant advances emerging in the past 20 years. For elite cyclists at race speeds on flat roads more than 90% of the athletes' power is expended overcoming aerodynamic drag [1]. The majority of the drag on the bicycle and rider system is attributed to the rider, typically 70% for a standard position. The remainder of the resistance is due to mechanical friction and rolling resistance. However, drag is dependent on the riding position [1]. As such, there are still significant performance gains to be made from optimising the aerodynamic performance of components such as the frame, handlebars and wheels. Additionally equipment selection offers an immediate performance benefit as it does not require the athlete to adapt, as with positional changes.

Initial concepts for aerodynamic wheels appeared during the 1980's with the introduction of the disk wheel. This was derived from knowledge of biplane undercarriage wheel fairings from early aerospace research [2]. Since this time there have been various different styles of wheels produced and numerous studies undertaken to evaluate their relative performance.

1.1 Frame of Reference

This paper adopts a definition of drag and side force relative to the motion of the bicycle, thus the drag is the force component that resists the forward motion of the bicycle. Some early studies of wheel performance treated the wheel as a flat plate aerofoil where yaw angle was treated as an effective angle of attack, with drag acting in the effective wind direction such that drag would increase with yaw angle [2].

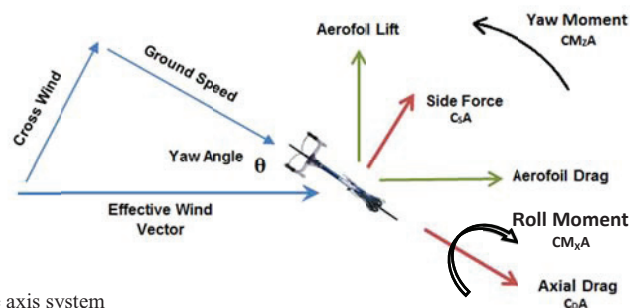


Fig. 1. Definition of bicycle axis system

As evident from Figure 1 the bicycle system acts much like a flat plate aerofoil at an angle of attack relative to the effective wind vector. Effective lift is generated which, in part, counteracts the axial drag force in a manner analogous to lift generated by a sail. Because of this phenomenon it is generally held that a disk wheel provides the optimal axial aerodynamic drag performance [3]. However, increased side force is also a corollary of an increase in aerofoil lift.

1.2 Research Limitation

Wheels have typically been tested in isolation which is not representative of real world conditions where they are subject to interference from the frame and rider as well as the ground plane. Additionally, many studies have ignored the increase in side force when evaluating aerodynamic performance and considered drag in isolation from other body forces and moments.

Studies by Jones [4] have shown that bicycle stability with a rider has little to do with the gyroscopic effect of the turning wheels as has often been suggested. It is the result of torque generated by the centre of gravity moving as the bike leans. Therefore large side forces and yaw and roll moments, especially acting on the front wheel, are likely to have a strong negative impact on bicycle stability, which must be handled by the rider. As such it is important for athletes to select the wheel that will deliver the optimum drag reduction without compromising handling or other performance characteristics. Practical experience has already led to disk wheels being banned from use as a front wheel in road events for many years and are even banned from rear wheel usage in certain events.

This paper aims to highlight the significance of loads other than axial drag acting on the bicycle system as a function of yaw angle and wheel selection. Of particular interest are yaw and roll moments and side force. It is suggested that the assessment of wheel performance and selection based solely on axial drag without consideration of other loads is an incomplete approach. The intention is that this will serve as a starting point for investigation into the effect of these loads on bicycle dynamics and handling. An additional product of this work is the comparison of certain specific wheel types as a part of the whole bicycle and rider system rather than wheel tests in isolation.

Note that this work did not assess the effect of these loads on bicycle dynamics. Nor was the local yaw moment about the front wheel measured, which will tend to have an effect on the steering stability of the bicycle. And no data has been presented as to the aerodynamic rotational resistance of different wheels. These parameters are important when modeling the overall aerodynamic performance of a bicycle and wheel.

2. Test Procedure

Testing was conducted in Monash University's large closed circuit three-quarter open jet wind tunnel. The jet exit, with dimensions of 2.6 by 4 m, resulted in a blockage ratio of less than 5% at 0° yaw angle for a bicycle with rider. The bicycle was mounted to a roller system by a pair of struts at the rear axle. Drive was provided to the front roller via a 200W electric motor with the rear roller connected by belt and speed matched to within 1%. Wind speed and wheel speed were maintained constant at 50km/h for all tests. Six axis force and moment components were measured using a set of four by three component piezoelectric transducers. The length scale adopted for the moment coefficients was the bicycle wheelbase. Existing research on standalone wheels indicates that C_S and C_D are approximately constant for most wheels for variations in wind and ground speed. Disk wheels however, do have a dependence on this relationship [5], [6], [7]. Variations in performance as a function of wheel to air speed should be the subject of future investigations.

2.1 Bike only testing

The bicycle was tested in isolation to eliminate any variations introduced by human test subject using a motor to drive the front and rear wheels. The test bike was a road specification time trial bike with typical tube cross sections and geometry. Cranks were fixed horizontally with saddle and pedals removed. Testing was conducted with a range of front wheels each with a flat sided disk rear wheel.

2.2 Mannequin Testing

Testing was conducted with an anthropomorphic cycling mannequin in the place of an athlete. The mannequin was tested with a different bicycle as it is not compatible with the reference bicycle used for

bicycle only tests. The mannequin legs were static during testing with the upper legs level as shown in Fig. 2. (b) Front and rear wheels were driven by the motor at 50km/h. The rear wheel used for mannequin tests was a convex style disk identical to the front disk used in all other testing rather than the flat sided rear disk used for bike only tests.



Fig. 2. (a) bicycle as used for bicycle only testing; (b) bicycle and mannequin setup

2.3 Tested Bicycle Wheels

Table 1. Specifications of tested wheels

Wheel Name	Rim Depth (mm)	Spoke Count	Tyre Type
Open Spoke	24	16	Clincher
Deep V 38	38	20	Tubular
Deep V 85	85	20	Tubular
Bladed 3 Spoke	55	3	Tubular
Convex Disk	NA	NA	Tubular
Flat Disk (Rear)	NA	NA	Tubular



Fig. 4. (clockwise from top left) open spoke, deep V 38, deep V 85, bladed 3 spoke, convex disk

3. Results

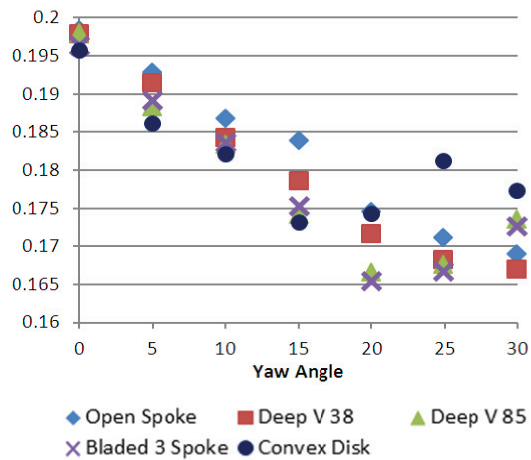
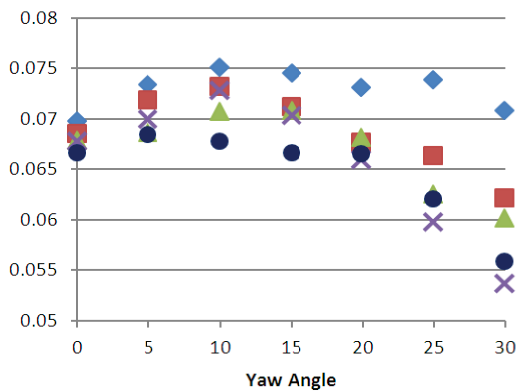


Fig. 5. (a) Bicycle only C_DA values; (b) mannequin C_DA values

It can be seen in Figures 5 (a) and (b) that the addition of the rider influences the axial drag results significantly. There is a difference in the shape of the C_{DA} curves and the expected magnitude differs as a result of introducing a rider into the system. For the bike only tests the disk is clearly a high performer although it is overtaken by the bladed 3 spoke above 20° yaw. In contrast with the mannequin in place the disk is nearly matched by the other deep section wheels at 15° after which point the drag increases significantly. This sharp increase may be due to the flow separating from the leading edge of the front wheel, although this behaviour was not observed without the mannequin. At small yaw angles the disk does not offer a large drag reduction benefit compared to the deep section wheels (Deep V 85 and Bladed 3 Spoke). These deep rims offer very similar performance across the range of yaw and both also exhibit the same minimum at 20° before also increasing and approaching the disk again. The shallower rims (Deep V 38 and Open Spoke) in contrast did not exhibit a local minimum up to 30° , however, it is possible that a similar point could occur if test procedures extended to higher yaw angles.

3.2 Side Force

Given that the bike appears to the freestream air as an aerofoil-like section, as yaw angle increases, the drag decreased but consequently the side force increased significantly. Both with and without a rider the side force coefficient curves display a linear relationship to yaw angle. C_{SA} values were similar in magnitude for both the bike only and mannequin tests.

The magnitude of the side force must also be considered. As yaw angle increased drag tended to drop but, as expected, side force increased linearly. As can be seen from the coefficients the side force was much higher than drag. At 15° yaw, the side force for all wheels was approximately double the drag force. For the mannequin fitted with twin disk wheels the side force at 10° was almost double the drag, being 44N compared to drag for this configuration being of the order of 23N.

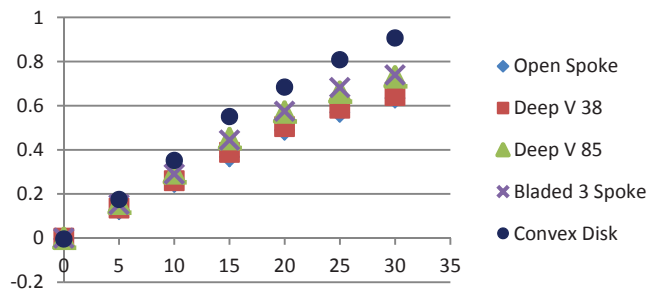


Fig. 6. C_{SA} values for the mannequin setup plotted against yaw angle

3.3 Moments

Roll moment coefficients have a linear trend for both bike only and mannequin test conditions. The magnitude of results as well as the relative performance was also similar for both cases. To indicate the importance of the roll moment on the bicycle dynamics it is possible to estimate the roll or lean angle required by the rider in order to counteract the imposed roll moment. With the mannequin fitted with two disk wheels the roll moment was 28Nm at 10° yaw angle. For an average sized rider this requires a lean angle of the order of 15° to balance the aerodynamic roll moment.

Yaw moment coefficient trend is similar both with and without rider interference. The addition of the rider appeared to have added a linear factor to all of the wheels such that the points have all shifted in the

positive moment direction. The pairing of the two shallow wheels and the two deeper wheels remains distinctly present in the mannequin results. As an indication of the size of the yaw moments induced on the bike, using the mannequin configuration with twin disks the yaw moment at 30° was 20Nm as modelled.

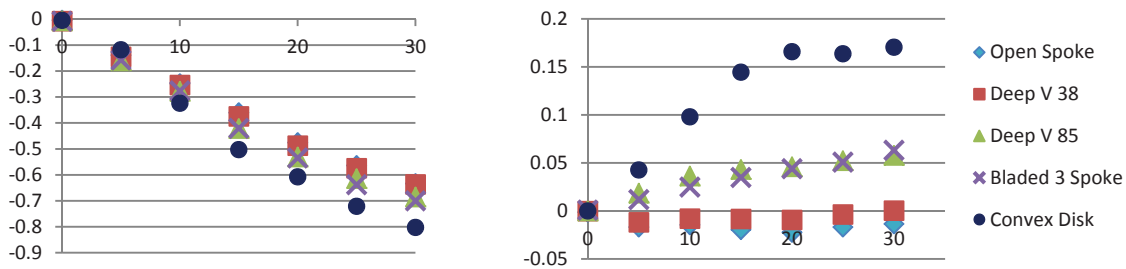


Fig. 7. (a) CMxA for mannequin setup against yaw angle; (b) CMzA for mannequin setup against yaw angle

4. Conclusion

A range of different front wheels, representative of common styles used in competitive cycling were tested in the wind tunnel and force and moment loads recorded. From the data it is apparent that there are significant differences in axial drag between the wheels and that appropriate wheel selection can lower the drag acting on the bicycle and rider system. The addition of the mannequin to the testing greatly influenced the trend of the drag curves, evidence of the interference generated by the rider. For this reason it is apparent that wheel performance should not be assessed from isolated wheel tests but from more comprehensive tests of wheels as a component in the bicycle and rider system.

Analysis of the other loads acting on a cyclist exposed to cross winds reveals significant loads in side force, roll moment and yaw moment. For all wheels side force was seen to be of similar magnitude to drag at 5° yaw and then increased linearly with yaw angle. Similarly the values of roll and yaw moments were significant even at low yaw angles. These additional loads, other than axial drag, have the potential to increase the rolling resistance of the bicycle as well as negatively impact the dynamics of the bicycle and affect the athletes handling and performance. Whilst it may be possible for certain riders to sustain these loads under steady conditions, the high cross wind conditions are more likely to occur in gusts making it more difficult for the athlete to control.

The results presented in this paper highlight that is not sufficient to assess the performance of a bicycle wheel using only axial drag as the criteria but rather consideration must be taken for the side force and roll and yaw moments imparted on the bicycle and rider.

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