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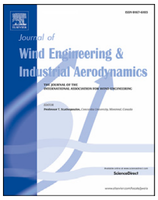

Aerodynamic drag in competitive tandem para-cycling: Road race versus time-trial positions

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ABSTRACT

An athlete's riding posture is a key element for aerodynamic drag in cycling. Tandem cycling has the complication of having two athletes in close proximity to each other on a single tandem bicycle. The complex flow-field between the pilot and stoker in tandem cycling presents new challenges for aerodynamic optimisation. Aerodynamic drag acting on two tandem road race setups and two track time-trial setups were analysed with computational fluid dynamics (CFD) simulations. For validation purposes, wind tunnel measurements were designed providing drag measurements from both tandem athletes simultaneously using a quarter-scale model. A max drag force deviation of 4.9% was found between the wind tunnel experiments and CFD simulations of the quarter-scale geometry. Full-scale CFD simulations of upright, crouched, time-trial and frame-clench tandem setups were performed. The drag force experienced by individual athletes in all investigated tandem setups was compared to that of solo riders to enhance understanding of the aerodynamic interaction between both tandem athletes. The most aerodynamic tandem setup was found to be the frame-clench setup which is unique to tandem cycling and had a C_DA of 0.286 m^2, and could provide an advantage of 8.1 s over a standard time-trial setup for a 10 km time-trial event.

1. Introduction

Tandem cycling is a sports branch governed by the International Cycling Union (UCI). Athletes who are visually impaired can compete in this discipline as the stoker, the rear athlete on the tandem bicycle. The lead athlete, denoted as the pilot, has full visual capabilities. The UCI has rules and restrictions over the suitability of an athlete to perform as a pilot, most notably, that members of a UCI professional team cannot perform as a tandem pilot, although it is allowed for former professional riders to do so (UCI, 2017).

Becoming faster by improving their aerodynamic profile is becoming a coveted prize for both elite and amateur cyclists. This is especially common within the core of elite cycling institutions across the world, both for able-bodied and para disciplines. Aerodynamic enhancements in elite able-bodied solo cycling have often traversed over to tandem cycling; in the form of aerodynamic wheel and frame designs, athlete apparel, and athlete posture refinements. However, little is known about the fundamentals of tandem aerodynamics and how the air flow interacts with the pilot and the stoker. Thus, there are likely opportunities for aerodynamic refinements specific to tandem cycling with alternative posture combinations, athlete apparel, and equipment design. Typical tandem postures for individual tandem athletes are often similar to postures adopted by solo athletes (Fig. 1). These include upright, dropped, crouched and various time-trial (TT) postures. Postures can be athlete specific depending on the anthropometrics and flexibility of the riders. Postures can also exist specific to tandem cycling, such as the frame-clench stoker posture (Fig. 1b); used particularly in timed events. Here, the stoker grasps the top tube of the frame (just behind or under the pilot's saddle) instead of holding the handlebars in a track event, in an effort to 'hide' behind the pilot to a greater degree. The UCI has specific restrictions limiting the movement of the handlebars and the saddle, which are used for athlete posture adjustments. Additional rules limit the

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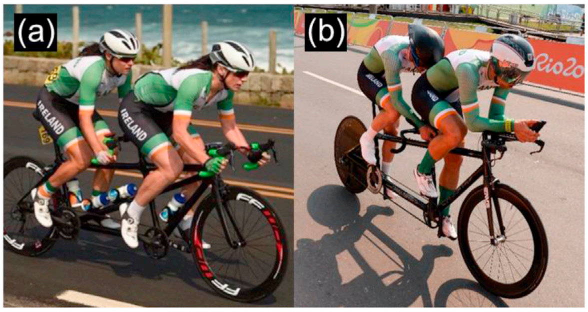

Fig. 1. (A) Irish female tandem team competing in a road race event, (b) Irish female tandem team competing in an outdoors TT event. The athletes in these photos were not involved in this research. (© Sportfile, Cycling Ireland and Paralympics Ireland, reproduced with permission).

dimensions of the tandem frame tubes, and aerodynamic devices or attachments are not permitted (UCI, 2017). These rules apply to both tandem and solo competitive cyclists, and are intended to keep the competition both fair and safe for all athletes participating.

CFD simulations and wind tunnel testing have been widely used in sports engineering in general and in cycling aerodynamics studies in particular (Blocken, 2014; Crouch et al., 2017). To the best of our knowledge, only Mannion et al. (2017) published a CFD and wind tunnel investigation on tandem cycling aerodynamics. Mannion et al. (2017) presented new guidelines for the modelling of tandem aerodynamics using CFD, and determined that the accurate prediction of flow separation is crucial for the appropriate assessment of tandem aerodynamics using CFD. Hence, a low average y* value less than 1 was recommended when generating a grid for a tandem cycling case study. Counter-intuitive and incorrect drag occurrences between the pilot and the stoker were observed when this guideline was not followed, with the stoker experiencing a larger drag force than the pilot. Mannion et al. (2017) also highlighted the impact of selecting a suitable turbulence model for tandem cycling aerodynamics, with the SST k-ω model (Menter, 1994) recommended for tandem cycling aerodynamics research. This is in agreement with the findings of Defraeye et al. (2010b) who also determined that the SST k-ω turbulence model provided the best overall predictions for solo cyclist aerodynamics, through obtaining detailed validation data from wind tunnel experiments with pressure measurements in addition to force and moment measurements.

Within the remaining literature, tandem cycling bears a close resemblance to a two-rider drafting formation; where two athletes cycle in close proximity and in-line with each other in order to provide a drag reduction primarily for the trailing cyclist. However, Blocken et al. (2013) determined through CFD simulations that the leading cyclist in a two-rider drafting formation can experience a reduction in drag by up to 2.6%. The benefit that a leading cyclist can gain was found to be enhanced if, instead of a trailing cyclist, a motorbike or a car was behind the cyclist (Blocken and Toparlar, 2015; Blocken et al., 2016). Indeed, a cyclist was found to experience drag reductions of up to 8.7% from a single following motorbike. The flow structures around two reduced scale in-line cyclists were analysed experimentally by Barry et al. (2016), who observed that the wake flow of the trailing cyclist was characteristic of that from a solo cyclist. Full scale wind tunnel experiments on two drafting cyclists were conducted by Barry et al. (2014), who found that the leading and trailing cyclists experienced maximum drag reductions up to 5% and 49% respectively.

Competitive solo cyclist postures and cycling positions have been widely researched in the literature, for both optimal power output and aerodynamics (Gnehm et al., 1997; Oggiano et al., 2008; Defraeye et al., 2010a; Underwood and Jermy, 2010; Chabroux et al., 2012; Fintelman et al., 2014a, 2015) where both computational and experimental methods have been successfully utilised to determine optimal postures for athletes. Defraeye et al. (2010a) conducted CFD analyses of solo cycling postures; upright, dropped and TT, and results from full-scale wind tunnel experiments were used to validate the computational results; C_DA values of 0.270 m^2, 0.243 m^2 and 0.211 m^2 were obtained for the upright, dropped and TT postures respectively from the wind tunnel experiments. Fintelman et al. (2014a) concluded that athletes should balance power output with aerodynamics, but determined that aerodynamic losses exceeded physical power losses at a velocity of 46 km/h, indicating that the importance of aerodynamics may outweigh the importance of power delivery at high speeds. Barry et al. (2015b) conducted wind tunnel experiments using solo cyclists to determine the influence of various athlete postures on aerodynamic drag. It was found that an optimal aerodynamic solution was for the athlete to bring his arms inside the silhouette of his torso and hips. It was also found that for an athlete in a dropped posture for a road race setup, the power requirement to maintain the same velocity can drop by 7% by lowering the head and torso to a crouched posture with horizontal forearms.

To the best knowledge of the authors, there has been no research on tandem posture variations conducted in the literature, and with no appearance in relevant review papers (Crouch et al., 2017; Lukes et al., 2005). Given the number of aerodynamic posture refinements that are applicable for a solo cyclist, there is an extensive scope of research for tandem athletes yet to be conducted. Readers are referred to Defraeye et al. (2010a) for a comparative summary of drag data for various solo cycling postures in the early cycling aerodynamics literature (1980's – 2000's).

The research presented here addresses the predominant gap in the literature regarding typical tandem athlete posture combinations. CFD simulations are performed by solving the 3D Reynolds-averaged Navier-Stokes (RANS) equations to explore the aerodynamics of two typical tandem road setups, and two tandem track TT setups. Fig. 1 shows two examples of competitive tandem cyclists with athlete posture combinations for a road race and outdoor TT event. Wind tunnel experiments are used to provide validation data for the CFD simulations.

2. Wind tunnel experiments

Wind tunnel experiments were devised to provide drag data on both the pilot and the stoker individually. Wind tunnel experiments were carried out in the aeronautical test section of the wind tunnel laboratory in the University of Liège, Belgium. A single athlete was 3D scanned using an Eva structured light scanner (Artec Europe, 2017) in a crouched posture, relevant to both pilot and stoker positions. By using the same geometrical athlete model for both the pilot and stoker positions, any inferred drag bias raised due to anthropometrical differences between two different athletes was removed. Quarter-scale 3D models were manufactured for the pilot, stoker and tandem bicycle by CSC cutting (Fig. 2). Similar to the set-up in Blocken et al. (2016), the model was raised 0.3 m from the bed of the test section by a sharp edged horizontal platform to limit the boundary layer development upstream of the test geometries. The resulting blockage in the 2 m × 1.5 m test chamber with

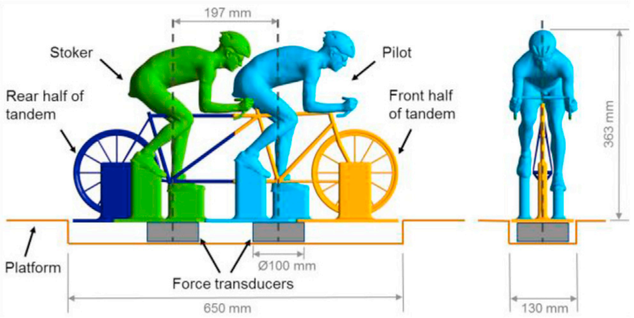

Fig. 2. Quarter-scale tandem geometry used for the wind tunnel experiments with the two force transducers.