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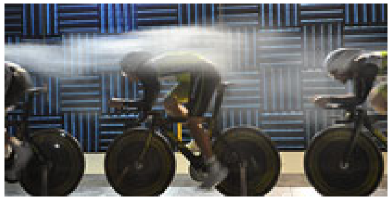
Drag kings: characterizing large-scale flows in cycling aerodynamics



A. E. Hosoi†

Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

In their recent publication Crouch *et al.* (*J. Fluid Mech.*, this issue, vol. 748, 2014, pp. 5–35) use wind tunnel experiments to quantify the large-scale vortical structures that develop as a cyclist progresses through a full rotation of the pedals. The authors identify asymmetries in the trailing vortex wake, which intensify as one leg straightens, as the primary source of drag variation over one pedal cycle. These new data suggest that targeted approaches to mitigate asymmetries in the trailing wake present an intriguing opportunity to reduce drag in cycling strategies and technologies.

Key words: drag reduction, flow–structure interactions, vortex shedding

1. Introduction: on drag and cycling

Ask a cyclist about drag and, somewhere in the lengthy exposition that your question unleashes, the cyclist is likely to use the phrase '. . . and what about legs?' Cyclists are painfully aware that legs are not very aerodynamic resulting in, one assumes, a tremendous amount of drag. Thanks to the recent article by Crouch *et al.* (2014) we may finally have an answer to this conundrum.

To appreciate the contributions of Crouch *et al.* (2014), it is important to recognize the central role of drag in cycling. (For a first-class primer on the science of cycling see Wilson 2004.) Forces generated by a cyclist riding in steady state on flat ground are balanced primarily by aerodynamic drag and rolling resistance. The magnitude of the aerodynamic drag force, D, the majority of which comes from the rider rather than the bicycle, can be estimated as

$$D = \tfrac{1}{2}\rho V^2 C_D A \tag{1.1}$$

where V is the cyclist's velocity, A is the frontal area (of both cyclist and bicycle), ρ is the density of air, and C_D is the dimensionless drag coefficient which may depend on the position of the cyclist, the Reynolds number, the cyclist's attire, etc. In contrast to the drag force, rolling resistance is roughly independent of velocity at speeds relevant to cycling.

† Email address for correspondence: peko@mit.edu

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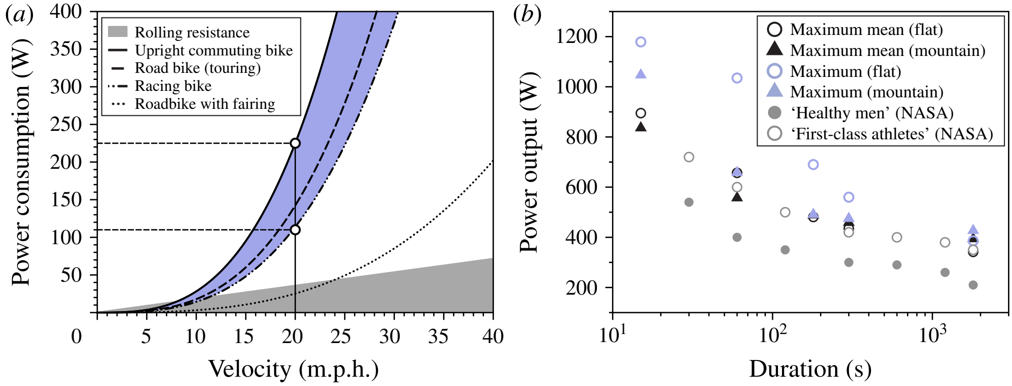

FIGURE 1. (*a*) Power required to overcome drag and rolling resistance for typical bicycle configurations. Here we have estimated the force due to rolling resistance as 4 N; this may vary with tyre pressure, tyre tread, tyre width, road condition, etc. but is typically of the order of a few Newtons. Drag coefficients and frontal areas for various configurations have been adapted from Wilson (2004). (*b*) Typical sustainable power by humans over varying time intervals. Grey points (NASA) have been adapted from Parker & West (1973); other points show data from 15 riders in the the 2005 Tour de France (Vogt *et al.* 2007). 'Maximum mean' indicates maximum power averaged over all 15 athletes; 'maximum' indicates the maximum power recorded out of the group of 15.

To illustrate the dramatic effect small changes in drag can have on performance, it is instructive to consider order-of-magnitude estimates of the relevant drag forces experienced by a cyclist and relate this to the power a cyclist can produce. Figure 1(*a*) shows power consumption, calculated as the drag force (1.1) multiplied by cycling velocity, for a variety of cycling configurations. Note that the rolling resistance rapidly becomes inconsequential above $\approx$15 m.p.h. hence, in racing conditions, large gains are more likely to be had in aerodynamic improvements rather than in tyre advances. Next, consider steady-state riding at 20 m.p.h. To maintain this velocity on a racing bicycle, a cyclist has to generate $\approx$110 W of power; if that same person switches to an upright commuter bike, they now need to produce $\approx$225 W, approximately double the power to maintain the same speed. This difference becomes even more pronounced through the use of other drag reducers such as aerobars, drafting, and skin suits.

To put these numbers in perspective, consider typical power generation capabilities of humans as shown in figure 1(*b*). Elite track cyclists can produce instantaneous powers as high as 2000 W; however, for sustained efforts, an average healthy person is limited to power outputs of $\approx$200 W. Hence, at 20 m.p.h., riding in a low-drag racing-bike configuration versus riding a commuter bike is the difference between an easy pedal around the park and riding at the edge of one's physical limits.

2. Overview: asymmetries in the wake

Although the importance of understanding and mitigating drag in cycling is indisputable, to date there has been a lack of careful characterization of the flow structures in the wake of a cyclist which have a large influence on aerodynamic drag. Crouch *et al.* (2014) have performed the first experimental study that systematically investigates large-scale flow structures that develop around a cyclist at various stages in pedal rotation, and analysed the impact of these structures on the concomitant

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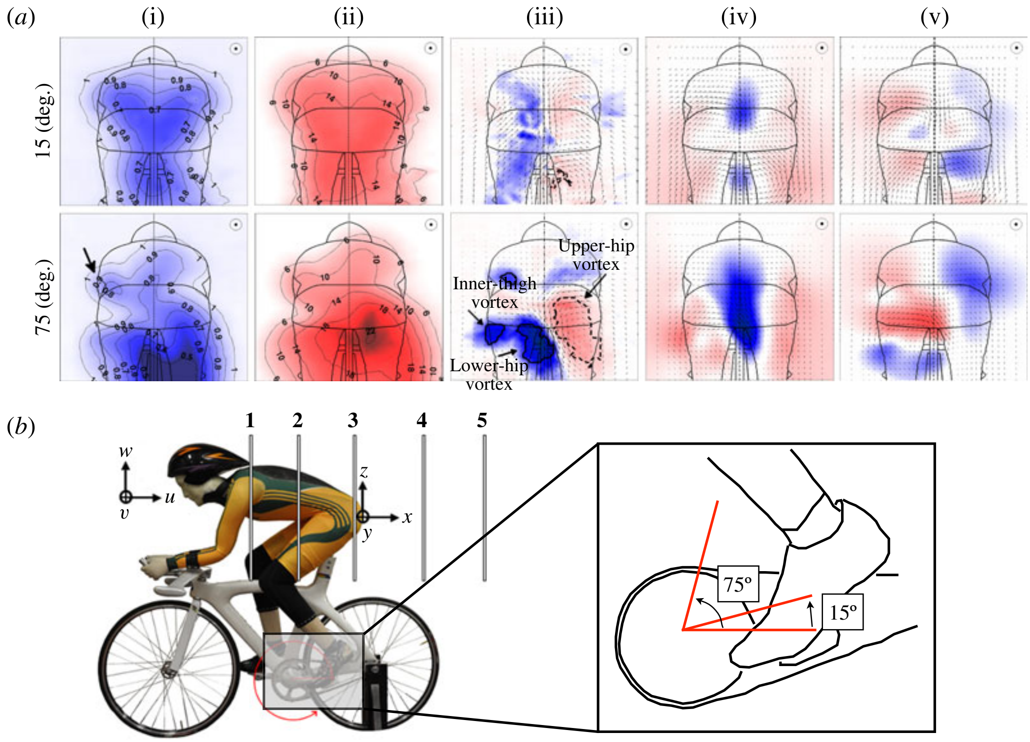

FIGURE 2. (*a*) Comparison of low- and high-drag flow structures: (i) streamwise velocity, (ii) principal turbulence intensity, (iii) streamwise vorticity with vortex boundaries, (iv) vertical component of velocity, (v) spanwise velocity. All of these images were selected to qualitatively illustrate the asymmetries that develop in the flow. For quantitative scales and other information, see Crouch *et al.* (2014). (*b*) Mannequin configuration, location of measurement planes, and definition of crank angle.

drag forces. As a first step, the authors consider quasi-steady motion, a reasonable assumption under many racing conditions, and visualize the air flow in the wake of the cyclist at various static positions of a mannequin's legs around the crank cycle (see figure 2*b*). The study is a tour de force of flow visualization, incorporating wind tunnel data from drag force measurements, wake structure surveys at discrete planes, skin friction flow visualizations, and time-averaged surface pressure measurements, to reconstruct full three-dimensional representations of the flow field around the cyclist.

The authors observe that drag force varies significantly (by approximately 20 %) throughout the pedal stroke with minima occurring at ≈15° and ≈195° (pedals roughly level and flat) and maxima occurring at ≈75° and ≈255° (one leg nearly straight). Image analyses reveal that the frontal area A of the cyclist and the bike varies by less than 2 % over a full pedal cycle, hence the bulk of the variation in drag must arise from variations in the drag coefficient C_D, which depends on the associated flow structures. Reconstruction of these flow structures reveals large-scale streamwise vortices, the formation, strength and interaction of which depend on leg position. The authors' key finding is the identification of asymmetries in the trailing vortex wake that arise at different points in the pedalling cycle. Low-drag configurations are associated with a symmetrical wake whereas asymmetrical vortex arrangements are observed in high-drag configurations. These asymmetries are highlighted in figure 2(*a*) which compares various flow fields at 15° and 75°, representing the low- and high-drag regimes respectively. The primary feature of the low-drag flow regime is the formation of weak streamwise vortices in a quadrupolar arrangement orientated symmetrically in the centreplane of the mannequin. This symmetrical arrangement results in a beneficial contraction of the wake owing to the interaction of similar strength vortices. In the high-drag flow regime the upper and lower vortex pair is orientated asymmetrically, no beneficial cancellation occurs in vortex strength, and hence the structures persist much further into the wake.

To quantify the change in drag associated with these structures, the authors use a swirling strength criterion to identify individual vortices and compute drag contributions from each of the measured vortices using a wake integral analysis. The swirling strength criterion identifies a pair of counter-rotating streamwise vortices as the primary feature of the wake flow in the high-drag asymmetrical flow regime (see figure 2*a* iii). In the low-drag regime however, the analogous large (but weak) coherent streamwise vortices are not picked out. Applying the wake integral analyses to the primary vortex structures in the asymmetrical regime reveals that these structures account for almost all of the variation in drag over the crank cycle.

3. Outlook

Crouch *et al.* (2014) have generated a tremendous amount of high-quality data associated with the large-scale flows around cyclists and have furthermore identified the vortical structures that are most detrimental (from a cyclist's point of view) in the pedalling cycle, which begs the obvious next question: How can we use use this information to improve cycling performance? The authors themselves propose 'The high dependence of the drag on the development and strength of primary vortices suggests that there is a great potential to improve rider aerodynamics through a targeted approach at reducing the drag associated with these flow structures'. This is an exciting idea which could lead to advances in racing strategies, skin suit design, or pedalling cadences targeted at mitigating asymmetries in the vortex wake. For example, could one design a skin suit with anisotropies in roughness between the upper and lower hip that influence separation to maintain (or at least increase) symmetry throughout the stroke? Are there riding styles or pedalling cadences that reduce asymmetries in the wake? When drafting, which alone can reduce aerodynamic drag by up to 47 % (see e.g. Kyle 1979), should one pedal in phase or out of phase with the rider one is following? The authors have provided a gold mine of data that allow us to begin to tackle these questions and potentially unleash an exciting new class of advances in cycling technologies.

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