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Collective behavior and the identification of phases in bicycle pelotons

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HIGHLIGHTS

- A method for identifying phases in bicycle pelotons is proposed.
- Collective behavior in bicycle pelotons is characterized by two distinct phases.
- Lateral synchronization occurs only in the high density phase.
- High velocities give rise to the low density "stretched" phase.
- Collective behavior reflects both energy savings and tactics in competition.

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ABSTRACT

As an aggregate of cyclists, a peloton exhibits collective behavior similar to flocking birds or schooling fish. Positional analysis of cyclists in mass-start velodrome races allows quantitative descriptions of peloton phases based on observational data. Data from two track races are analyzed. Peloton density correlates well with cyclists' collective power output in two clear phases, one of low density, and one of high density. The low density "stretched" phase generally indicates low frequency positional-change and single-file synchronization. The high density "compact" phase may be further divided into two phases, one of which is a laterally synchronized phase, and another is a high frequency and magnitude positional-change phase. Phases may be sub-divided further into acceleration and deceleration regimes, but these are not quantified here. A basic model of peloton division and its implications for general flocking behavior are discussed.

1. Introduction

A peloton may be defined as a group of cyclists that are coupled together through the mutual energy benefits of drafting, whereby cyclists follow others in zones of reduced air resistance. Although the interactions among individual cyclists are in principle very simple – each cyclist takes a turn leading and then returns to the pack – the collective behavior of the peloton is very complex. This is characteristic for social interactions in general. These interactions usually involve only a few individuals at a time, yet may give rise to non-trivial global phenomena, like opinion formation, cultural dissemination, evolution of cooperation, and the emergence of hierarchy in initially egalitarian societies [1–4].

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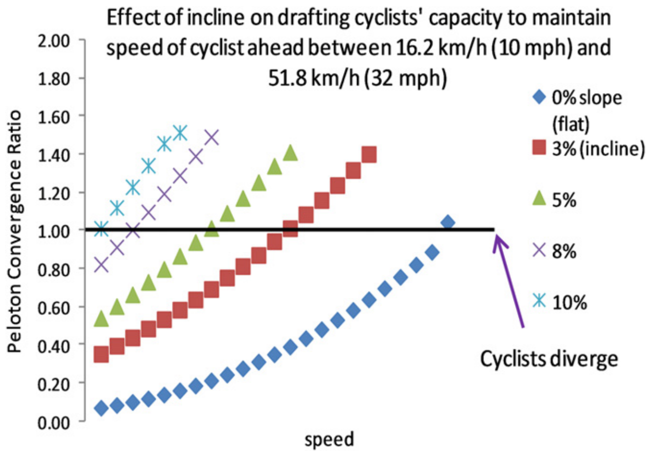

Fig. 1. Illustration of the application of the peloton convergence ratio (PCR), demonstrating the effect of increasing slope on a drafting cyclist's capacity to maintain the speed of a front cyclist. Using an approximate energy savings of 1% per 1.6 km/h (1% per miles/h) starting at 16.2 km/h (10 miles/h) to a maximum of 51.8 km/h (32 miles/h), each point represents 1.6 km/h (1 mile/h), also corresponding to 1% energy savings by drafting below PCR = 1.00. *Source:* Figure adapted from Ref. [11].

Investigations of conceptually similar complex systems have a long tradition in condensed matter physics. Among the most important features of complex systems is the emergence of phase transitions [5], which can be traced back to the Ising model [6]. In fact, the comprehensive understanding of the collective behavior of systems at phase transition points can be considered as a major intellectual revolution of statistical physics during the past century. Strong interactions between particles result in increasing correlation lengths, which render microscopic details of the system irrelevant from the viewpoint of its macroscopic behavior. As a result, universality classes have been established in which seemingly very different systems behave identically.

The parallelism between interactions between particles and spins and the interactions among living organisms is the motivation behind many applications of statistical physics methods and models to describe large-scale complex social and natural phenomena. The applications range from fractal growth [7,8] to correlations in economy [9] and animals on the move [10]. Here we wish to extend the scope of this theory to the collective behavior in bicycle pelotons, which to the avid cyclists among the readers will be familiar as the stage for intriguing tactical and positional competition.

1.1. Coupling model for cyclists in peloton

Peloton dynamics have been characterized by four major phases, and oscillations among phases were modeled as occurring within threshold ranges of a parameter called the "peloton convergence ratio" ("PCR") [11]. The Peloton Convergence Ratio describes the coupled power-output relationship between two cyclists, one being in a non-drafting position, and the other being in a drafting position. The Peloton Convergence Ratio quantifies the power reduction benefits of drafting at a given speed.

$$\mathrm{PCR} = \frac{\left[P_{\mathrm{qfront}} - \left(P_{\mathrm{qfront}} * \left(\frac{D}{100}\right)\right)\right]}{P_{\mathrm{MSO}}}. \qquad (1)$$

In (1) P_{qfront} is the power output of the front rider at the given speed (the same power output that would be required by the drafting (following) rider to maintain the speed set by the front rider, *were the following rider not drafting*—hence "required output"); D is the percentage of energy saved by drafting; P_{MSO} is the maximal sustainable output (MSO) of the drafting cyclist, subsequently defined in more detail.

PCR is more simply described as a ratio of the following rider's required output for the given speed, minus drafting benefit D, over her maximum output, where the speed and drafting component are determined by the front rider. Differences in equipment, body frontal surface area or body position, are ignored.

The required output, as set by the non-drafting front rider, may exceed the maximal sustainable output of the following rider. However, the *actual* output of the following rider at the speed set by the front rider is that which has been reduced by drafting benefit D. When PCR < 1, the following rider's actual output is less than her maximal sustainable output, and she maintains the speed set by the front rider. When PCR > 1, the required output exceeds the drafting rider's actual output and her maximal sustainable output, and the two riders will de-couple, as shown in Fig. 1.

For example, a drafting (following) cyclist with a hypothetical maximum sustainable output of 349 W (based on the range of power outputs reported by Ref. [12]) on a flat, windless, course can maintain the speed of a rider ahead (who may or may not also be drafting behind other riders) up to about 32 miles/h (51.8 km/h), above which a stronger rider will ride away from the weaker cyclist, when PCR > 1. On a 3% grade, the same drafting cyclist will be able to maintain the speed of a rider ahead up to about 22 miles/h (35.4 km/h), above which a stronger front rider will pull ahead. At grades of 10% or more