

Self-Organized Coupling Dynamics and Phase Transitions in Bicycle Pelotons

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Abstract

A peloton is a group of cyclists whose individual and collective energy expenditures are reduced when cyclists ride behind others in zones of reduced air pressure; this effect is known in cycling as 'drafting'. As an aggregate of biological agents (human), a peloton is a complex dynamical system from which patterns of collective behaviour emerge, including phases and transitions between phases, through which pelotons oscillate. Coupling of cyclists' energy expenditures when drafting is the basic peloton property from which self-organized collective behaviours emerge. Shown here are equations that model coupling behaviours. Environmental constraints are further parameters that affect peloton dynamics. Phases are defined by thresholds of aggregate energy expenditure; shown here are two different, but consistent, conceptual descriptions of these phase transitions. The first is an energetic model that describes phases in terms of individual, bi-coupled and globally-coupled energy output thresholds that define four observable changes in peloton behaviour. A second, economic model incorporates competition and cooperation dynamics: cooperation increases as power outputs and course constraints increase and population diminishes, and where competition and cooperation for resources results in peloton divisions into sub-pelotons whose average fitness levels are more closely homogeneous.

Introduction

A peloton may be defined as two or more cyclists riding in sufficiently close proximity to be located either in one of two basic positions: 1) behind cyclists in zones of reduced air pressure, referred to as 'drafting', or 2) in zones of highest air pressure, described here alternately as 'riding at the front', 'in the wind', or in 'non-drafting positions'. Cyclists in drafting zones expend less energy than in front positions. These zones are located either directly behind or beside at angles to other cyclists, depending on wind direction. For large pelotons (approx. >6), a proportionately higher number of cyclists will be in drafting positions, while a lesser proportion will be in front positions.

Energy expenditure when drafting as a single is

reduced by approximately 18% at 32km/hr (20mph), 27% at 40km/hr (25mph), when drafting a single rider, and, in a group of eight riders, by as much as 39% at 40km/hr in a group of eight riders (McCole et al. 1990). At the elite level, speeds of 40 to 50km/hr on flat topography are common, and pelotons of 100 or more cyclists are common. Because there is an approximate energy savings of 1% per mph when riding behind one rider, for convenience speeds are shown in miles per hour.

I. The Energetic Model

Coupling occurs between cyclists when one or more seek the energy-saving benefits of drafting. A cyclist's power requirement to overcome wind resistance is proportional to the cube of his or her velocity (Burke, ed. 1996). In order to overcome wind resistance, approximately one percent of total energy expenditure required to overcome wind-resistance is reduced per one mile an hour by drafting behind a single cyclist, while greater reductions occur by riding in the middle of a larger pack (Hagberg and McCole 1990), although below approximately 10mph, drafting benefit is negligible (Swain 1998; Figure 1).

Cyclists' power output is not determined only by speed; it may vary according to position (drafting or non-drafting), riders' speed being equal. Also, speed falls in proportion to the slope of the road (Swain 1998), while power output may remain constant. Conversely, speed may be high on a descent, but power output low.

Cyclists' Power Output and Drafting Benefit

By taking advantage of the energy savings benefits of drafting, cyclists' energy expenditures/power outputs are thus coupled, and by alternating peloton positions to optimize energy expenditures, cyclists can sustain higher speeds for greater durations. This effectively narrows the differences in output capacities among cyclists in a peloton. This difference-narrowing is the basis for tactics

and strategy in bicycle racing as cyclists seek to exploit competitors' limited output capacities, while expending their own most efficiently. While these tactics and strategies are not strictly self-organized, self-organized energy dissipation dynamics also emerge, including phase changes at critical energy/power output transition thresholds, which is the focus of the discussion here.

To illustrate the effective narrowing of cyclists' output distributions, we can demonstrate the range of cyclist's (elite competitors) approximate maximum output capacities as derived from time-trial data, and contrast those distributions with the results of mass-start races in which cyclists couple outputs and finish together.

In time-trials, competitors commence at timed intervals and are not permitted to draft. Time-trial data reveals that, in any given elite-level race, distribution of individual capacities is Gaussian, and the range is approximately 17 percent between weakest and strongest cyclists. Time-

trialing ability is a strong, but not the only, indicator of a cyclist's capacity to keep pace within a peloton. Narrowing of this distribution is facilitated by drafting benefits, demonstrated by mass-start race data in which the range between the winner and last finisher is substantially smaller than the distribution among time-trialing cyclists, often less than five percent, and among a whole peloton finishing together, or smaller groups (sub-pelotons), is effectively zero.

Individual Time trials (TT)^a

Event	Length (km)	Fastest time	Speed (km/h)	Slowest Time	Speed (km/h)	Percent Difference
2003 Four days of Dunkirk	19	23.08	49.4	28.86	39.5	20.0
2003 World Championships	41.6	51.28	48.6	60.17	41.5	14.8
2004 Van de Panne	13.7	16.62	49.5	19.95	41.2	16.7
2003 Vuelta Espana	53.3	62.05	53.2	72.78	43.9	14.7
2003 Vuelta Espana	43.8	53.56	49.0	68.12	38.6	21.4
2003 Giro d'Italia	42.5	54.55	46.7	66.07	38.6	17.4
2003 Giro d'Italia	33	38.07	52.0	46.66	42.4	18.4
2003 Tour de France	6.5	7.43	52.4	8.53	45.7	12.9
2003 Tour de France	47	58.53	48.2	71.32	39.5	17.9
2004 Tour de Langkawi	18	21.63	49.9	26.97	40.0	19.8
Mean	31.8		49.9		41.1	17.4

Road Races (RR)^b

Event (stage)	Length (km)	Fastest time	Speed (km/h)	Slowest Time	Speed (km/h)	Percent Difference
2004 Tour of Langkawi (1)	112	2.58	43.4	2.58	43.4	0
2003 4 days of Dunkirk (1)	189.5	4.58	41.4	4.82	39.3	4.98
2003 Tour of Georgia (1)	223	5.47	40.8	5.55	40.2	1.44
2003 Giro d'Italia (1)	201	5.27	38.1	5.30	37.9	0.56
2003 Settimana Ciclista (1)	151.3	3.60	42	3.95	38.3	8.86
2003 Giro del Capo (1)	132	3.55	37.1	4.03	32.8	11.91
2003 Solano (1)	139	3.78	36.8	4.32	32.2	12.50
2003 Amstel Gold	250	6.02	41.5	6.15	40.7	2.11
2003 Tucson Bicycle Classic	168	4.10	41.0	4.18	40.2	1.91
2003 Tour de France (1)	168	3.73	45.0	3.80	44.2	1.84
Mean	173.4		40.7		37.9	4.61

Table 1. Percent differences in first and last finishing TT times and RR times (www.cyclingnews.com, 2004); random selection of TT, RR. For RR, higher percentage differences occurred in hilly races where drafting advantage was negated for significant periods; lower percent difference in largely flat races where drafting was significant.^aTime units are minutes in decimal notation. ^bTime units are hours in decimal notation.

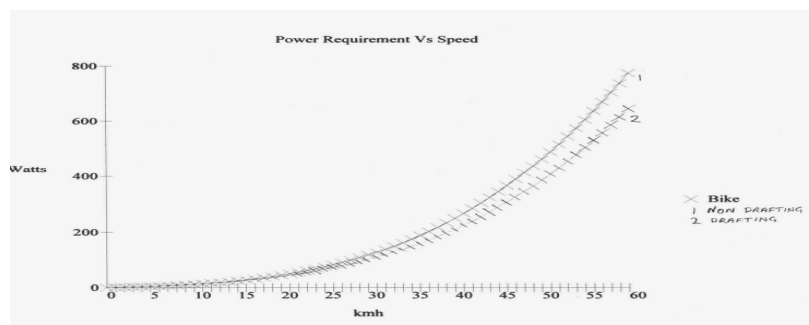


Figure 1. Power requirements for cyclist in non-drafting position and cyclist in drafting position. Curve for non-drafting cyclist 75kg (bicycle and rider), rolling friction coefficient 0.004, 0 gradient, air-density 1.225kg/m³, at 20mph (32km/h), drag co-efficient of 0.5, frontal surface area of 0.05m². Curve for drafting cyclist based on constants except drag co-efficient of 0.41, for an 18% reduction of drag coefficient. Drag coefficients from www.analyticcycling.com, and parameters and calculations for graphs and graphs from PowerCalc, found at www.machinehead-software.co.uk.

In Table 1 the average time difference between first and last place road race times is 4.61 percent, compared to 17.4 percent in individual time-trials. Results of mass-start races also show the majority of competitors frequently finish within two percent of the winner’s time, especially during level-topography races when maximum drafting opportunities exist for virtually the entire race. Among cyclists within a sub-peloton, all of whom finish together, receive the same finishing time under rules of bicycle race governing bodies, and as such the difference is zero. From the perspective of collective dynamics, a group of cyclists given the same finishing times is more than merely practical (i.e. easier for timing officials), but reflects the unitary, holistic nature of the peloton.

Coupling Description

Coupling capacity between two cyclists is well described by the ratio between the difference between power outputs of two cyclists at any given time, and the drafting advantage for speeds at those times. A simplified occurrence where maximum sustainable outputs between riders are offset by the drafting advantage, referred to here as the Peloton Divergence Ratio (PDR), is given by

$$PDR = (W_a - W_b/W_a) / D/100$$

Where W_a is the maximum sustainable power output (watts) of cyclist A at any given moment; W_b is the maximum sustainable power of cyclist B at any given moment (assuming $W_a > W_b$); $D/100$ is the percent energy savings (correlating to reduced power output) due to drafting at the speed travelled. This is called a divergence ratio because it reveals the critical threshold at which coupled riders de-couple.

“Maximum sustainable output” refers to outputs sustainable for specific limited durations and defined by physiological thresholds: absolute maximum output (sprint) may be sustained for less than ten seconds, while a sub-maximal effort, but over anaerobic threshold is sustainable for approximately two minutes; an aerobic output may be sustained for hours (American Sports Medicine Institute 2009). The examples in this article generally reflect anaerobic efforts $>10s$ and $<2min$, but can be scaled to apply to all threshold maximums.

A modified, more powerful version of PDR, referred to here as the Peloton Coupling Ratio (PCR), is given by:

$$PCR = 1 / [W_a / (W_a M_a - (W_a M_a * D/100))]$$

Where:

W_a is the maximum sustainable power output (watts) of drafting cyclist for given speed;

M_a is the proportion of the drafting rider’s power output to her sustainable maximum output at any given speed when not drafting;

D is the percent energy percent energy savings (correlating to reduced power output) due to drafting at the speed travelled (Table 2, Table 3).

The value 1 is a ratio of the output of the front rider to her maximum power output for the speed given (i.e. 1/1)

Unlike PDR, which is limited to situations where the stronger rider is in front and both riders are at maximum outputs, PCR describes all ranges of power output combinations between coupled riders as against the maximum output of the front riding cyclist, and expresses degrees of coupling strength between cyclists at any coupled speed. The lower the value of PCR, the greater the degree of coupling strength (Table 3, figure 2).

Riding speed (km/h)	10	20	32	40	50
Estimated reduction (%)	7	18			32
Measured reduction (%)			18	27	
Approximate incline gradient for maximal power output at speeds noted	18	8	4	2	0
Example rider A - max power output in each situation (watts)	450	450	450	450	450
Example rider B - max power output in each situation (watts)	420	420	420	420	420
PDR = (Wa-Wb/Wa) / D/100	.07/.07 (1.00)	.07/.18 (0.39)	.07/.18 (0.39)	.07/.27 (0.26)	.07/.32 (0.22)
Example rider C - max power output in each situation (watts)	390	390	390	390	390
PDR = (Wa-Wc/Wa) / D/100	.13/.07 (1.86)	.13/.18 (0.72)	.13/.18 (0.72)	.13/.27 (0.48)	.13/.32 (0.41)
Example rider D - max power output in each situation (watts)	360	360	360	360	360
PDR = (Wa-Wd/Wa) / D/100	.20/.07 (2.86)	.20/.18 (1.11)	.20/.18 (1.11)	.20/.27 (0.74)	.20/.32 (0.63)
Example rider E - max power output in each situation (watts)	330	330	330	330	330
PDR = (Wa-We/Wa) / D/100	.27/.07 (3.86)	.27/.18 (1.50)	.27/.18 (1.50)	.27/.27 (1.00)	.27/.32 (0.84)

Table 2 Example coupling ratios, applying PDR. Estimated and measured reduction in energy expenditure at various speeds (Kyle, C. 1979; McCole, S.D. et al, 1990; Burke, E., 1996), approximate corresponding slope gradients for maximal power outputs at those speeds, and four examples of coupling ratios. Above PDR threshold 1 (bold italics) peloton divergences occur. Below this threshold, riders are coupled. ^cPower output largely dependent on body weight and other factors – approximations here based on 75kg rider with 0.5m² frontal area, coefficient of wind drag 0.5 dimensionless, air density 1.226 kg/m³, coefficient of rolling resistance 0.0004 dimensionless, slope force 25 kg m/s², pedal force 293.1 kg m/s² (Compton, T. 2004 www.analyticycling.com)

M is a relative value derived from cyclists' maximum sustainable speeds without drafting, which value is applied to determine cyclists' respective power outputs at those speeds. M is based on speed to be consistent with drafting advantage, D, which is a function of speed and not power output; power outputs are then used to reflect the reduction of output required when D is incorporated, while speeds may be the same between riders.

In applying PCR versus PDR, there is no distinction between the positions of stronger versus weaker riders – they can be in either position. PCR allows us to find the coupling degree of coupled cyclists by measuring current output of a drafting rider, and the effect of D, as against the maximum sustainable output of the rider in front, and not only in the limited case when a stronger rider is in

front at maximum sustainable output and a weaker rider is behind and at maximum sustainable output.

Both PDR and PCR indicate that divergence between cyclists *necessarily* results when the maximum output of the following cyclist is less than the output (maximum or not) of the rider ahead minus the fractional drafting benefit. This will never occur when a stronger rider is drafting behind a weaker rider, (Table 3 and Figure 1), who enjoys the double advantage of drafting and being stronger. When the weaker rider in front reaches maximum speed/output, the riders may change positions and the stronger rider may drive the speed higher while the weaker rider drafts (Figure 2). When this occurs (switching positions), the PCR curve breaks to a higher range as the weaker rider's output is closer to maximum.

As for PDR, the threshold PCR between cohesion and disintegration is thus 1. Divergence occurs when cyclists proceed at different speeds, outside others' drafting range. Thus when $PCR > 1$, A pulls away from B (divergence), de-coupling them, at least temporarily; when $PCR < 1$, cyclists converge.

current speed (mph) coupled Riders A and B	D/100	Max Spd A	Wa	Ma	Wa Ma	Wa Ma * D	WaMa a - (Wa Ma * D)	Wa/ WaMa - (WaMa a * D/100)		Max Sd B	Wb	Mb	Wb Mb #	Wb Mb* D	WbMb - (WbMb * D)	MaxSdB / WbMb - (WbMb * D)	PCR=1/ (Wa/ WaMa - (WaMa * D/100))
16	0.16	29	500	0.55	275	44	231	2.16		20	345						0.46
17	0.17	29	500	0.58	290	49	241	2.07		20	345						0.48
18	0.18	29	500	0.62	310	56	254	1.96		20	345						0.51
19	0.19	29	500	0.65	325	62	263	1.9		20	345						0.52
20	0.2	29	500	0.68	340	68	272	1.83		20	345						0.54
riders change positions																	
21	0.21	29	500							20	345	1.05	362	76	286	1.2	0.83
22	0.22	29	500							20	345	1.1	380	84	296	1.16	0.86
23	0.23	29	500							20	345	1.15	397	91	306	1.13	0.89
24	0.24	29	500							20	345	1.2	414	99	315	1	0.91
25	0.25	29	500							20	345	1.25	433	108	325	1.06	0.94
26	0.26	29	500							20	345	1.3	449	116	333	1.04	0.97
27	0.27	29	500							20	345	1.35	466	125	339	1.02	0.98
28	0.28	29	500							20	345	1.4	483	135	347	0.99	1.01
29	0.29	29	500							20	345	1.45	500	144	355	0.97	1.03

Table 3. Hypothetical data for two coupled cyclists riding from 16mph to 29mph. Wa is arbitrarily set max output for cyclist A of 500W at 29mph on flat windless course. Wb is B's max output of 345W at 20mph. M is fraction of current output based on current speed/max speed on flat, no wind. D is approx. percent energy savings due to drafting at speed travelled. WaMa is current output at current speed for rider A. WbMb is current output at current speed for rider B. Weaker rider B is in front, non-drafting position for speeds 16mph – 20 mph. When rider B reaches max, riders switch positions, and stronger rider is in front. #Rider B *required* outputs if she were to proceed at that speed; by drafting she can reduce output by D, so her speeds at max output increase to her max 345W. Note discrepancies due to rounding.

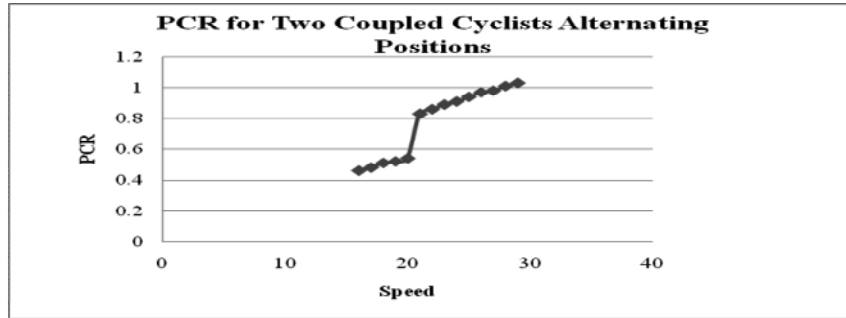


Figure 2. Peloton Coupling Ratios, based on hypothetical data (Table 3) for two cyclists with arbitrarily selected maximum non-drafting outputs of 500W at 29mph on flat course, and 345W at 20mph on flat course, as plotted against increasing speed of coupled riders. Stronger rider is drafting at speeds 16mp to 20mph. When weaker rider in front reaches maximum output at 20mph, riders change position so stronger rider is in front and weaker rider drafts. PCR increases at lower values and rate when stronger rider drafts, and curve breaks when they switch positions. PCR then increases at higher values and rate, and when D no longer compensates for difference between stronger rider’s and weaker rider’s maximums, PCR exceeds 1 and riders de-couple.

When divergence occurs and PCR is >1, the speed of a following cyclist falls proportionately to the drafting benefit enjoyed when the riders were coupled:

$$S_b = S_d - (S_d * D)$$

Where S_b is speed of weaker rider B after divergence and no longer in a drafting position; S_d is speed of rider B when drafting. D is the percent energy savings at speed travelled. This shows that once rider B falls out of drafting range, her speed will fall rapidly (though power output may remain constant) and the distance between rider A and B increases according to a new ratio of their respective outputs that is minus the benefit of D .

Global Coupling

The foregoing describes coupling effects between two riders. As an aggregate of more than two riders, all cyclists within a peloton are at $PCR < 1$ relative to each other, a further defining feature of a peloton. When a rider or a group of riders (sub-pelotons) falls out of drafting range of other riders, whether ahead, among, or

the behind the peloton, this may be described as a local instability, and riders are at $PCR > 1$. Short term (approx <2 seconds) instabilities frequently result in a longer term peloton divisions and the formation of sub-pelotons. Longer term (>2 seconds) instabilities may be described as disintegration.

Disintegration occurs to varying degrees: a single rider may fall outside drafting range of others; several riders may separate from the main peloton and form a sub-peloton, or many individuals or sub-pelotons may result from large scale disintegration.

Phase Changes

Peloton phases are first-order transitions, characterized largely by changes in density at critical collective output thresholds (Ball 2004). Because competitors in a bicycle race commence as a group, an initial cohesive phase state (i.e. bunching that occurs at the start line and immediately upon race commencement) is not self-organized. As a race proceeds, however, phases oscillate aperiodically through four self-organized transitions:

Phase	Description	Properties
I	Cohesive but disordered	Relatively low speed (PCR well <1), low power output, low energy expenditure, minimal coupling by drafting. Low density; high isotropy (Prigogine, 1996). Unstable and prone to increasing speeds/outputs and increasing density.
II	Peloton rotation/rolls	Increased speeds/power output/energy expenditure, but sub-physiological threshold. Maximum density, anisotropic (Prigogine, 1996). System bifurcates to global convection roll dynamics or peloton rotations. Critical transition occurs at mean PCR <1 but begins to approach 1 for most cyclists in peloton. Stable, comprising largest proportion of peloton duration.
III	Stretched, synchronized	Speeds synchronize; riders align in elongated single line. While shape has changed completely, density is topologically equivalent to phase II. Mean PCR near 1. High power output/ energy expenditure. High anisotropy. Critical transition occurs when majority of riders are coupled at or very near physiological thresholds (Figure 4).
IV	Disintegrated	Mean PCR >1 . No cohesion, riders are generally de-coupled. High isotropy. Physiological thresholds and coupling capacity (the critical threshold) is exceeded for sufficient duration and among sufficient number of cyclists to induce disintegration. Low density, but high output. Unstable and prone to relatively high reductions in speed and reintegration through phase I.

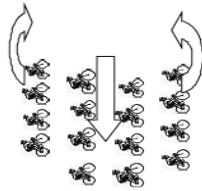


Figure 3. Phase II rotations, convection dynamics. Curved arrows indicate general direction of rotation – riders pass up peloton peripheries and effectively move toward centre. Central arrow indicates effective direction of travel as riders on peripheral trajectories pass and move toward the centre.



Figure 4. Phase III Single pace-line. The above single pace-line is self-organized in racing conditions as a result of near maximal outputs of riders, as opposed to an *organized* paceline in which riders deliberately establish an ordered line, primarily during training, or team time trials.

Figure 5. Phase IV peloton disintegration. Photo shows finish as riders separate at above threshold output and where PCR >1 .

Each of these states is a function of the total energy output of the peloton system as speeds increase or decrease according to the slope of the course. Individual and total energy output is optimized by collective drafting opportunities. During Phase I, cyclists' outputs are generally below maximums, resulting in PCRs <1 . Phase II is a mixed-phase, where some cyclists accelerate and others decelerate in a rotational fashion; but the mean PCR <1 for all cyclists. Phase III exhibits stretching, where PCRs approach 1, indicating a highly ordered, intermediate threshold state between disintegration and cohesion.

Further Discussion on Rotation Dynamics

As indicated, coupling represents the primary peloton dynamic from which self-organized behaviours emerge. However, coupling must also be considered in combination with secondary dynamical factors such as positional adjustments to avoid collisions, as well as a forward motion imperative, whereby riders endeavour to maintain close proximity to the front (identified as a 'peloton resource' in part II on the economic model). Further secondary factors, not considered further in this analysis, include subjective human motivation and desire, among others.

This combination of factors gives rise to self-organized peloton dynamics, such as cyclist rotations in which riders advance up the lateral extremes of the peloton as riders in central positions fall toward the back (Figure 3). This may be described by the following ratio:

$$PR = PCR_f/PCR_s$$

Where PR is peloton rotation; PCR_f is the average PCR of cyclists traveling at faster passing speeds; PCR_s is the average PCR of cyclists traveling at slower speeds as they are being passed. While there are continuous smaller rotations even during Phase 1, only at a critical PCR threshold does PR bifurcate to a global scale, leading to Phase II dynamics. At this scale, PR occurs at an as yet unidentified PR ratio and speed, and possibly at a critical minimum peloton size, but the average peloton PCR < 1. There may also be a power law describing the magnitude and frequency through the range of peloton rotations, though this has not been established.

The equation implies that there may be countless adjustments in speed occurring among riders passing or being passed, but as long as passing is occurring, all those passing may be given the same average speed, as can those riders being passed. A higher ratio implies faster rotations and higher speed and/or power output.

This phase may be described as a convection roll (Rayleigh, 1916), dissipative dynamic (Prigogine, 1996) as energy output ("heating") occurs on peloton extremities, while falling output occurs effectively backward through the middle ("cooling"; Figure 3).

II. The Economic Model

An economic model incorporating PCR and cooperation/coupling rules is presented generally here, although further details are left for subsequent analysis.

The Drafting Resource

Like natural organisms which compete for food or other resources to survive, there are at least two resources within a peloton for which cyclists compete to survive (or to win). The most significant resource is the energy savings offered by the drafting effect of the peloton, as discussed. A savings in energy is a physically tangible (i.e. experienced directly through physiological feedback) resource in the case of a peloton in which the benefits of the resource significantly outweigh the energetic costs of acquiring it.

For cyclists to maintain access to the drafting resource often requires short term maximal or near-maximal efforts, as they must frequently sprint or ride above their anaerobic threshold for short durations to remain coupled with riders ahead, but that effort is rewarded by higher average speed (as well as the higher average speed of every rider in the peloton). Thus one functional effect of the drafting resources offered by the peloton is to narrow significantly the range between the strongest and weakest by the finish (as discussed in the energetic model).

The Front Position Resource

The second resource is less physically tangible, but nevertheless highly relevant in the context of a mass-start bicycle race: close proximity (CP) to the front of the peloton. CP is distinguished from non-drafting positions at the front of the peloton, and represents positions *near* the front that allow riders simultaneously to draft as well as remain in tactically advantageous positions to respond to other cyclists' "attacks" (quick accelerations) or the final sprint for the finish. This is an example of a 'positional resource' (Morrell, 2008). Here, cyclists compete for a limited number of positions that are tactically advantageous.

The best positions are at the front of the peloton, where "breakaway" attempts may be launched, or from which the winner ultimately emerges – the farther back a cyclist is, the less likely it is that he or she can win the race. Experienced riders explain that cyclists should try to stay in the top ten to 15 places - positions for which pelotons consisting of well over 100 riders may compete. Because peloton boundaries represent the fastest route for achieving the front positions, these positions are also highly sought. But maximum drafting benefit lies within the peloton, and so cyclists must continuously weigh the higher energy costs of advancing up peloton extremities to gain positional advantage against the energy savings of central maximum drafting positions. Experienced cyclists will attest that continually fighting for the front is energetically costly, but it outweighs the potentially

greater cost of trying to close gaps ($PCR > 1$) when they inevitably form at positions farther back.

Both drafting and CP resources are valuable, but CP is a scarcer resource, because there are few such positions available.

Cooperation and Resource Consumption

Ultimately, it is through the cooperative (or coupled) efforts of riders which result in raising the average speed of each rider in the group, narrowing the range between the weakest and strongest rider.

The process of matching cyclists' energetic costs in seeking/maintaining access to resources to the available resources may be described as proceeding through three primary phases representing a continuum of cooperation (C), ranging from little cooperation at low outputs and high population, to increasing/optimal cooperation at high but sub-maximal outputs in smaller populations. The optimal cooperation phase precedes a highly unstable transition phase where small increases in outputs can elevate $CR > 1$, resulting in peloton divisions and a self-organized sorting process when riders of nearly equal strength form sub-groups which, in turn, are highly cooperative in attempting to reintegrate groups ahead, or remain ahead of groups behind.

Reeve and Ildobler (2007) discuss this process of within-group and between-group tug-of-war; they note that selfish within-group competition increases as group size increases, as within-group relatedness decreases and as between-group relatedness increases. This occurs among peloton dynamics: cooperation increases as group size decreases and fitness range narrows among riders, and between-group competition increases.

Reeve and Ildobler indicate this kind of cooperative investment is characteristic of a superorganism and, in this sense, a peloton undergoes a further transition to a superorganism



Figure 6. Phase III transition. Sorting of main peloton into echelons of riders of nearly equal fitness. Riders are forced to cooperate by the cross wind and road width constraints which minimize free-riding opportunities.

The three primary phases of C:

- I. Low power outputs (well below physiological fatigue thresholds), low consumption of resources (low costs), low peloton density. Cyclists exploiting the efforts of others (free riders) are abundant and riders at the front are not concerned about excess use of energy.
- II. Increasing rider costs as outputs approach $PCR = 1$; increasing competition for resources, increasing self-organized cooperation and sharing of resources as riders alternate time spent at the front in the wind. Peloton density increases. Maximum cooperation occurs during this phase.
- III. Weaker riders are at physiological thresholds, even when maximizing drafting resources (highest costs). At this threshold, cooperation breaks down and the peloton splits ($PCR > 1$). Peloton sorting then occurs, and the peloton divides into smaller groups consisting of riders at $PCR < 1$ and near equal fitness. Maximal cooperation occurs among these sub-groups whose fitness levels are closer to the average of the group (Figure 6).

Conclusion and Directions for Future Work

As a complex dynamical system of interacting agents (cyclists), a peloton is a phenomenon which has not been rigorously analyzed. There are studies of the drafting advantages of cyclists, their exercise intensities, and much discussion of cycling as a sport, but there is little that describes the interactions between cyclists and the patterns which emerge.

Established here is the basic unit of peloton dynamics -- coupling through drafting -- and a model is presented. While phase changes are identified and predicted, data has not been compiled to establish their precise critical thresholds. Data of peloton power outputs over the duration of race events will best establish these particular thresholds. Computer models should also be refined.

In particular, critical coupling (PCR) thresholds should be identified delineating various phases; power law for frequency and magnitude of roll dynamics should be identified; existence of hysteresis through oscillations should be identified; oscillation signatures identified; and shifts in dynamics through course gradient changes, among others.

In addition, the strategies of cyclists, based on allocation of energy resources, are amenable to a game theory approach under the economic model, and further critical thresholds of cooperation dynamics and phase transitions may be identified.

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