

A deceleration model of bicycle peloton dynamics and group sorting

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Abstract

Extending earlier computer models of bicycle peloton dynamics, we add a deceleration parameter by which deceleration magnitude varies as a function of cyclist strength. This model is validated by applying speed data from a mass-start race composed of 14 cyclists, and running simulation trials using 14 simulated cyclists that generated positional profiles which compare well with the positional profiles observed in the actual mass-start race data. Keeping constant the speed variation profile from the mass-start race as introduced into the simulation, a set of simulation experiments were run, including: varying the number of cyclists; varying the duration of a single near-threshold output event; and varying the course elevation. The results consistently show sorting of pelotons into smaller groups whose mean fitness corresponds with relative group position, i.e. fitter groups are closer to the front. Sorting of pelotons into fitness-related groups provides insight into the mechanics of similar group divisions within biological collectives in which members present heterogeneous physiological fitness capacities.

Keywords: Peloton, cyclists, sustainable output, group sorting, biological collectives

Introduction

Pelotons are groups of cyclists coupled by power-output reduction (energy-savings) benefits of drafting. Pelotons may include as many as 200 cyclists, as observed in mass-start bicycle races such as the Tour de France [1].

A cyclist's power requirement to overcome wind resistance is proportional to the cube of his or her velocity [2]. Power requirements when drafting, for a single rider are reduced

by approximately 18% at 32km/h (~20mi/h), 27% at 40km/h (~25mi/h); and by as much as 39% at 40km/h among a group of eight riders [3]. For two riders, drafting benefit is negligible at speeds below 16 km/h (10mi/h) [4].

When cycling in groups, cyclists' sustainable speeds increase according to drafting benefits, leaving the sustainable power output unchanged for drafting cyclists. For example, based on power output ranges reported in [5] a drafting cyclist with a hypothetical maximum power output of 349W can sustain the speed of a stronger rider up to ~52km/h (~32mi/h) on a flat, windless course, and yet may sustain only approximately 41km/h under the same conditions, without drafting benefit¹.

Cyclists' maximal sustainable power outputs ("MSO") depend upon individual physiological capacities, and vary as a function of the duration of the output [9]. A cyclist's MSO may be determined if her maximal oxygen uptake parameter (VO_{2max}) is known [10]. For the cyclists whose data is applied in this paper, VO_{2max} values are unknown. However, reasonable estimates of these cyclists MSOs were derived from publicly available sprint times and corresponding power outputs, as discussed further.

Pelotons frequently divide into smaller groups, as shown in Figure 1. Generally, pelotons divide when the power-output reduction benefit of drafting is no longer sufficient to compensate for the differences in strength between weaker and stronger cyclists. For example, as course inclines increase (i.e. hills), drafting benefit diminishes due to reduced speed, while power-output remains high; in such conditions pelotons tend to divide frequently and into numerous groups, as shown in Figure 1 (lower left). For flatter terrain pelotons tend to divide less frequently, as in Figure 1 (lower right), indicating that drafting benefits are sufficient for weaker cyclists to sustain the speeds of stronger cyclists.

¹ Approximated by reference to drafting equations in [6, 7], and speed to power conversions in [8].

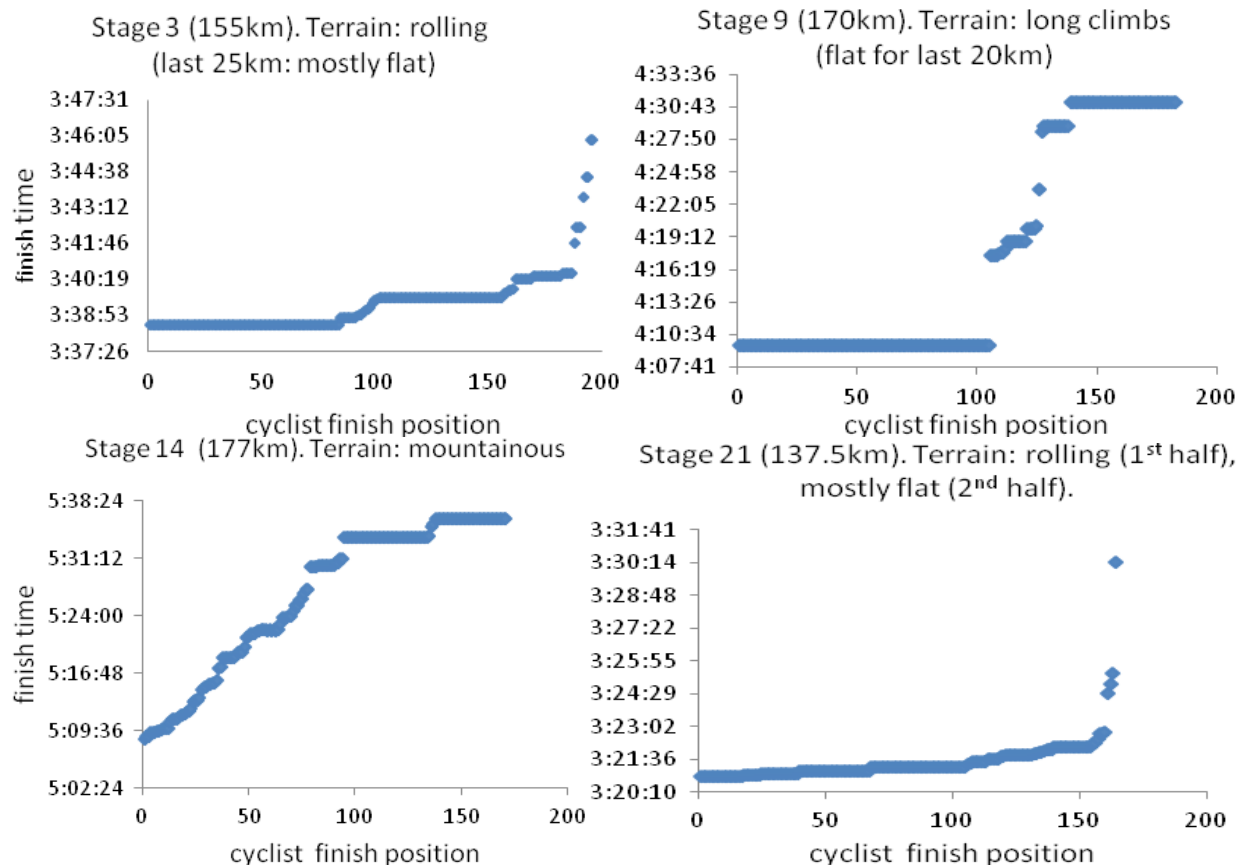


Figure 1. Results of four stages of the 2014 Tour de France [1]. Flat or rolling courses with flat finishes tend to produce a relatively small number of groups of riders finishing together; such groups tend to finish within narrow time intervals (upper left, and lower right). Mountainous races with uphill finishes tend to produce more numerous, smaller groups (lower left); courses with long climbs and relatively long flat finishes tend to produce larger, less numerous groups than mountainous races, but which finish within wider time intervals than flat races (upper right).

However, even at high speed on relatively flat courses, pelotons may also undergo division due to fatigue induced at sustained high speed or due to coupling instabilities, or a combination of these factors. Coupling due to drafting is inherently unstable as cyclists continuously adjust their positions, periodically exposing following riders to the wind. This necessitates a rapid response from following cyclists in order to maintain optimal drafting position. Following cyclists are particularly susceptible to increased wind exposure on circuitous or narrow courses; cross-winds, or high density configurations when riders compete for optimal drafting positions. High density situations are particularly unstable due to the high probability of crashes at a critical density threshold.

Theory/calculation

To demonstrate the mechanics of peloton divisions, we further develop the “peloton-convergence-ratio” (*PCR*) expression [11]:

$$PCR = \frac{P_{front} - (P_{front} * \frac{D}{100})}{MSO} \quad (1)$$

This refers to the situation of two coupled riders: the non-drafting front-rider sets the pace; the follower enjoys the drafting benefit and maintains the same speed, at a lower power output. Two-cyclist coupling is a simple principle that readily generalizes to more complex, many-rider interactions. Moreover, all drafting cyclists are coupled to both the rider immediately ahead who provides the drafting benefit for the follower, and also to a single non-drafting cyclist at the front of the peloton, or a relatively small number of non-drafting cyclists at the front who set the pace. Here we refer to a “front-rider” as a non-drafting cyclist who sets the pace; a “leader” is a cyclist immediately in front of a drafting rider, but who herself may be drafting behind other riders.

In (1), “ P_{front} ” is the power output of the front-rider as she sets the pace within the coupled system. “ D ” expresses the follower’s energy savings due to drafting, as a fraction (percentage) of the front-rider’s power output. Thus, the follower’s required power output is ($P_{front} * (D / 100)$), assuming approximately equal factors affecting required power output for all riders, aside from drafting². Finally, MSO is the maximal sustainable power output for the follower: should P_{front} exceed MSO , the follower will be unable to sustain the leader’s (and front-rider’s) speed and must decelerate to a speed less than or equal to that speed representative of the limitation of MSO .

A drafting cyclist may operate at or below MSO . If she is at MSO while drafting but conditions change (e.g., the rider falls too far behind or too far to the side of the optimal drafting position, with respect to the leader), then the follower must decelerate. If she is below MSO while drafting but temporarily falls outside drafting range, she can increase power output to maintain the pace of the leader as long as she does not exceed MSO .

PCR can also be expressed in the form:

$$PCR = \frac{P_{front} - [P_{front} * (1 - d)]}{MSO} \quad (2)$$

² The following parameters are used to determine cyclists’ power output (in W): frontal area of cyclist = 0.639m²; drag coefficient = 0.5; coefficient for power transmission losses and losses due to tire slippage = 0.015; air density = 1.226 kg m³; coefficient of rolling resistance 0.004; mass of rider and bicycle = 75kg; coefficient for velocity-dependent dynamic rolling resistance (CrV), approximated 0.1; coefficient for the dynamic rolling resistance, normalized to road inclination CrV *cos(β); rolling friction plus slope pulling force (Frg) = 9.8 * Wkg * ((crr * cos gradient) + (sin gradient)); gradients variable

where the term $1 - d$ is written instead of $D/100$; and where d is the drafting coefficient.

$$d = 0.62 - 0.0104d_w + 0.0452d_w^2 \quad (3)$$

Equation (3) is from Olds [8], who referred to this coefficient as " CF_{draft} " (which he derived from data presented in [9]).

Rearranging (2) the front-rider's power output (" P_{front} ") is:

$$P_{front} = \frac{MSO * PCR}{d} \quad (4)$$

To find the threshold representing the greatest speed a cyclist is able to maintain, we convert " P_{front} " to velocity (V_{front}) using power output relationships and parameters as in [12; Appendix A] and [13]. A (weaker) follower must decelerate to a speed less than or equal to the speed corresponding to $PCR = 1$, so we want to know her power output corresponding to her physiological threshold, MSO , while drafting (i.e., $PCR = 1$):

$$P_{threshold} = \frac{MSO}{d} \quad (5)$$

This is identical to (4) with the assumption $PCR=1$. Then, " $P_{threshold}$ " represents power output reduction due to drafting when $PCR = 1$.

Thus the expression $P_{front} - P_{threshold}$ allows us to obtain the follower's speed that corresponds to her MSO . First converting " $P_{threshold}$ " to an equivalent speed (" $V_{threshold}$ ") using the same power-speed relationships as before [12, appendix A], we then take the difference of the two values (6), obtaining the difference between the speed set by the (stronger) front-rider and the (slower) speed which is the maximal speed available to the (weaker) rider:

$$V_{reduction} = V_{front} - V_{threshold} \quad (6)$$

" $V_{reduction}$ " thus represents the deceleration magnitude for the following rider, in the event her required output to maintain the speed of a front-rider corresponds to an output that exceeds her MSO ($PCR > 1$).

When cyclists decelerate to keep their output at or below MSO , they usually slow to an output below, but not exactly at the threshold (on an individually varying basis). Therefore it is reasonable to add a small random magnitude of deceleration (6), as follows:

$$V_{reduction} = V(P_{front}) - V(P_{threshold}) + \Delta V \quad (7)$$

Equation (7) summarizes our model for determining a speed update to apply to the weaker (following) rider, given the circumstance $PCR > 1$ (that is, the follower is no longer able to keep pace with the front-rider). In (7), “ $V(P)$ ” term is a velocity “ V ” expressed as a function of a power “ P ”, and Δ is the aforementioned small (positive) random (individual) deceleration quantity.

We incorporate (7) into the computer peloton dynamics model by Ratamero [14]. In addition, some adjustments to Ratamero’s cohesion and separation rules are given. Finally, we also adjust Ratamero’s drafting parameter, to account for increased drafting benefit for multiple drafting cyclists [14].

1.1 Simulation design

In [11] positional profiles of 14 female cyclists in a 30 lap (333m/lap) velodrome race (the “Points Race”) was shown, as in Figure 2. For the purpose of the model introduced here, the speed data from the Points Race are analyzed to derive parameters for the simulation experiments.

Accordingly, 200m sprint times of 11 of the 14 cyclists in the Points Race, achieved during sprint trials prior to the Points Race, were used to determine equivalent power outputs (in W) required to sustain their 200m average speeds. The average power output of the 11 cyclists (397W) was used to represent the values of three cyclists in the Points Race who did not participate in the sprint trials.

These power outputs were then multiplied by a coefficient of 0.82. This coefficient 0.82 is the fraction (399W/485W) where 399W is power at 48km/h and 485 is power at 51.4km/h. The former (48km/h) is the maximum speed sustained for a duration greater than 30s (39s) representing the maximal aerobic power threshold sustainable for a duration of between 30s and ~5min [6]. The latter (51.4km/h) is the absolute maximum speed attained during the Points Race (15min 53s in duration).

These power outputs were then applied as *MSO* data for all simulation experiments involving 14 simulated cyclists. The power outputs are, in descending order:

47	45			40	40	39		39		37		305
9	8	435	412	2	0	7	397	7	393	2	356	351 .

For all simulation experiments involving greater than 14 cyclists, random power output values in the range 305W-479W were used (the lower and upper thresholds represent the two extreme *MSOs* from the Points Race data). Thus, small variations in mean *MSO* are observed, between experiments.

MSO data accuracy is further limited because there are multiple variables determining power output. For example, the course surface roughness, the mass and frontal surface area of the cyclist, and the absence or presence of wind (even at low speeds) will affect power output as a function of speed. Here, these parameters were not precisely determined, although it is possible to assume reasonable estimates for their values (see

footnote 2). For the races, minimal wind was observed. Further, *MSO* constantly changes for each cyclist as fatigue temporarily reduces *MSO* [15]. Consequently, it was not practical to obtain accurate empirical measures of *MSO* power outputs; in this light the values discussed represent reasonable estimates.

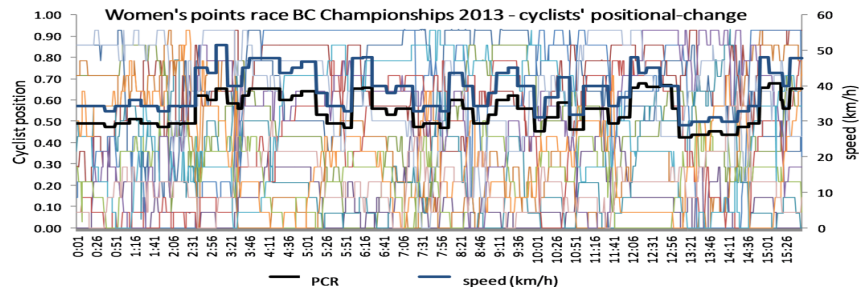


Figure 2. Women's 30-lap points race: positional-profiles. The heavy blue curve is speed; the heavy black curve is the Peloton Convergence Ratio (PCR).

Introducing *MSO* and speed data as observed in the Points Race, and running a series of tests to fine-tune cohesion/separation parameters established in [14], we obtain typical parameter profiles, as follows:

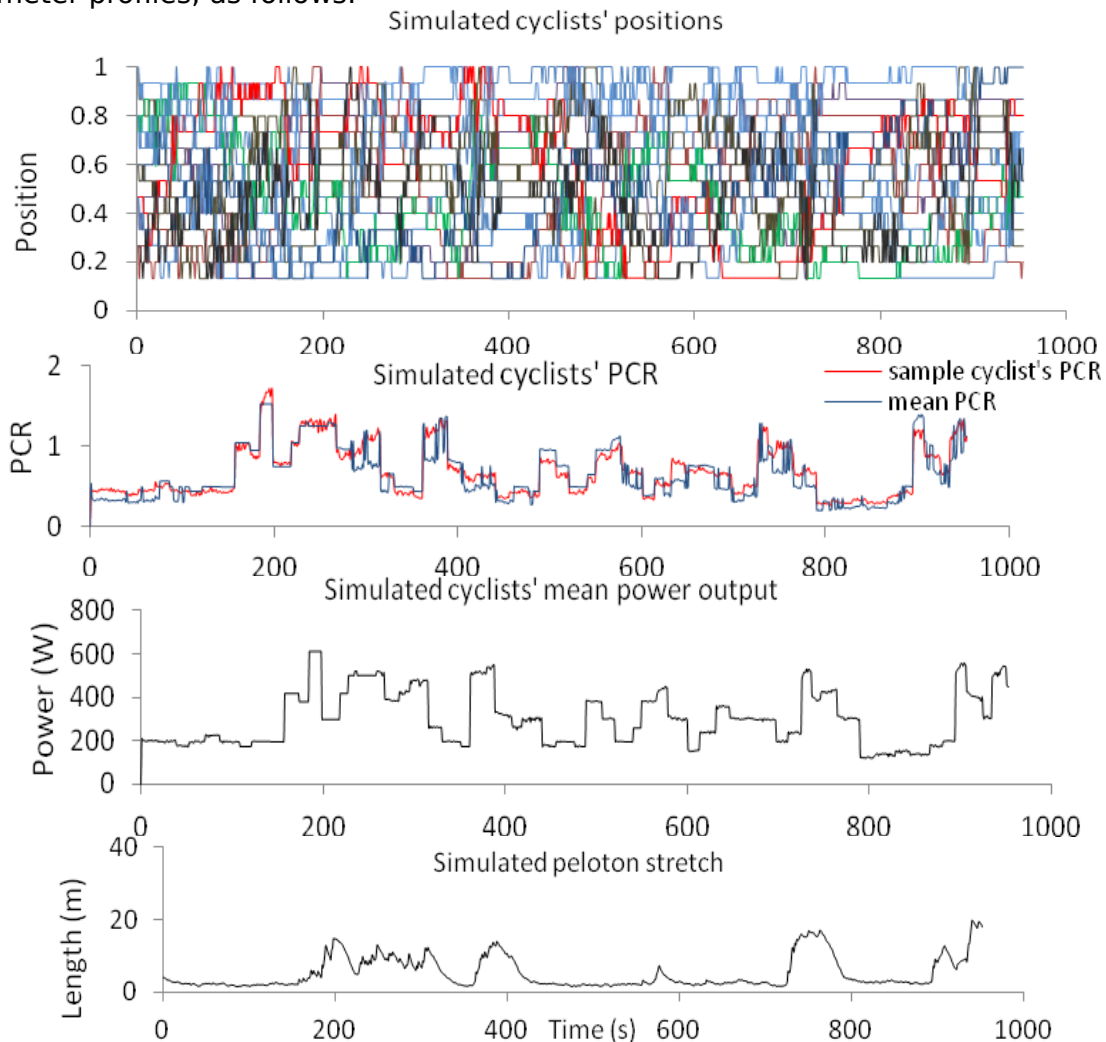


Figure 3. Typical simulated race profile for 14 cyclists, using *MSO* and speed data derived from the Points Race data. In the upper graph, the zero (front-most) position was not computed. Peloton stretching is represented by parallel line patterns which indicate cyclists travel in single-file. The mean power output (among all cyclists) is shown in the third plot, while a simulated peloton stretch parameter is shown in the lower image (plotted against time, in seconds).

The cohesion and separation parameters (“CS parameters”) adjust the range in which the “attractive force” of centroid (mean x-y coordinate) positioning applies [14]. CS parameter values are small relative to the actual forward speed parameter values [14] and for this model the CS parameter values are also small relative to deceleration parameter values. The CS parameters were balanced heuristically against the deceleration parameter values, seeking to obtain the profile shown in Figure 2.

Keeping constant the speed profile as observed during the Points Race, the following simulation tests were run:

	Variable	Runs
14 cyclists	3% hill	10
	One 4% hill	“
	Flat	“
25 cyclists	3% hill	“
	One 4% hill	“
	Flat	“
50 cyclists	3% hill	“
	One 4% hill	“
	Flat	“
100 cyclists	3% hill	“
	One 4% hill	“
	Flat	“

Table 1. Outline of the simulation protocol. For each run, the precise speed profile derived from the Points race data (Figure 2) was coded into the algorithm as a constant parameter.

The above sequence of tests was run, in which we increased the size of the simulated peloton from 14 riders to 25, 50, and 100 riders, with no change in hill gradient. We also varied the durations at which cyclists proceeded at specific power outputs by varying the hill gradient in two circumstances: 1) for the entire simulation (“3% hill”) (simulation time equivalent to 15:53 minutes); 2) for a single period of 19 seconds when cyclists travelled at 39.9km/h, during which the gradient was increased from zero to 4% (“One 4% hill”). Immediately prior to the One 4% hill period, cyclists travelled at 51.4km/h for 14s. By increasing the gradient to 4% for a further 19s immediately following the absolute maximum speed of 51.4km/h, simulated cyclists were forced to sustain nearly the same absolute maximum power output for a total of 33s. Thus the One 4% hill was incorporated to test the effect on peloton dynamics of an extended period of sustained

near maximal power output. In all three sets of experimental simulations, speeds were not varied from the original speed profile obtained from the Points Race. For each combination we observed whether peloton division and/or sorting occurred.

Results and Discussion

There is remarkable agreement between the actual Points Race positional profile (Fig 2), and the simulated positional profile, according to the upper image of Figure 3. These profile similarities validate model parameters. Realistic collective positioning according to cyclists' inherent abilities (*MSO*), speeds, and output ratios (*PCR*) emerge, as in Figure 4.

There is also general agreement in the nature of the peloton divisions in comparing the Tour de France results (Figure 1) with the simulation experiment results. Where power output is sustained near threshold for all riders (e.g., for “3% hill” gradient, as in Figure 4, middle image) pelotons tended to divide into smaller groups, as also shown in Figure 1 (lower left: “mountain” finish). Overall, flat courses produce small numbers of groups, supporting the results indicated in Figure 1 (upper left and lower right images).

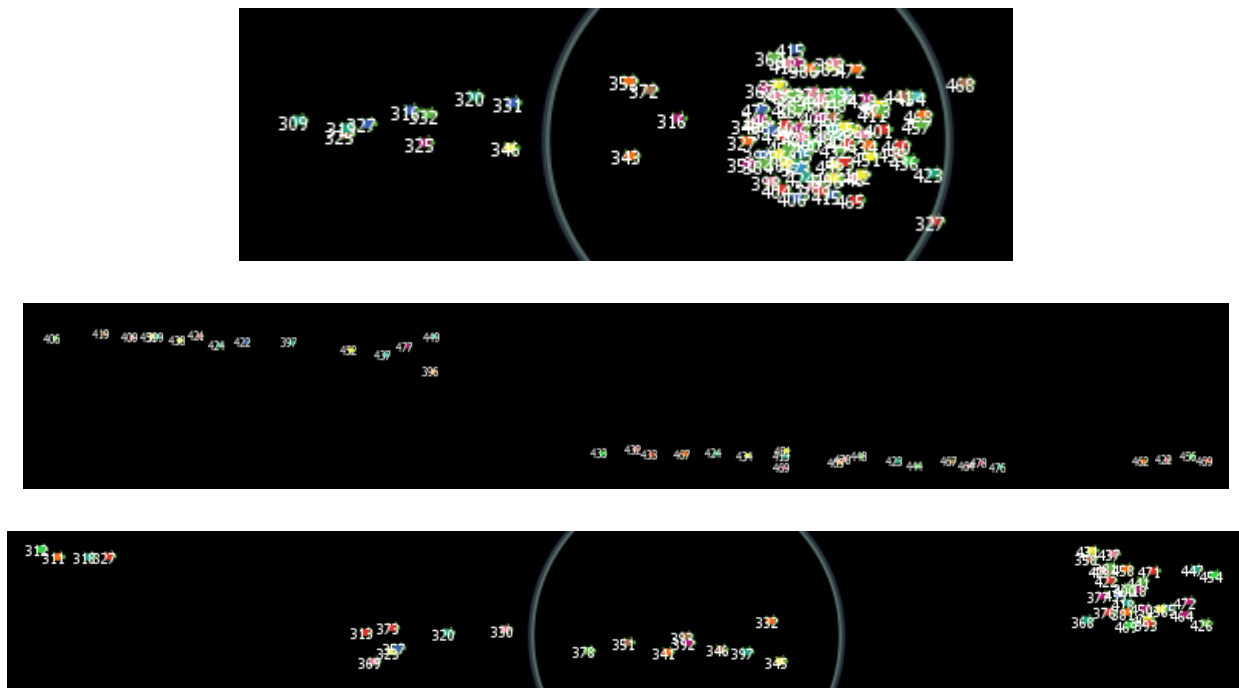


Figure 4. Three typical simulated bicycle peloton dynamics simulation end states. The upper image shows 100 cyclists in a simulation with “flat” terrain; low peloton stretch and low group division are observed (individual *MSO* values are shown). The middle image shows a segment of 100 cyclists travelling on “3% hill” terrain: high peloton stretching and division into three main groups is observed. The lower image shows 50 cyclists with “one 4% hill” terrain slope variation: peloton stretching and division are observed: one high density group is seen at the front (far right) as stretched groups follow behind.

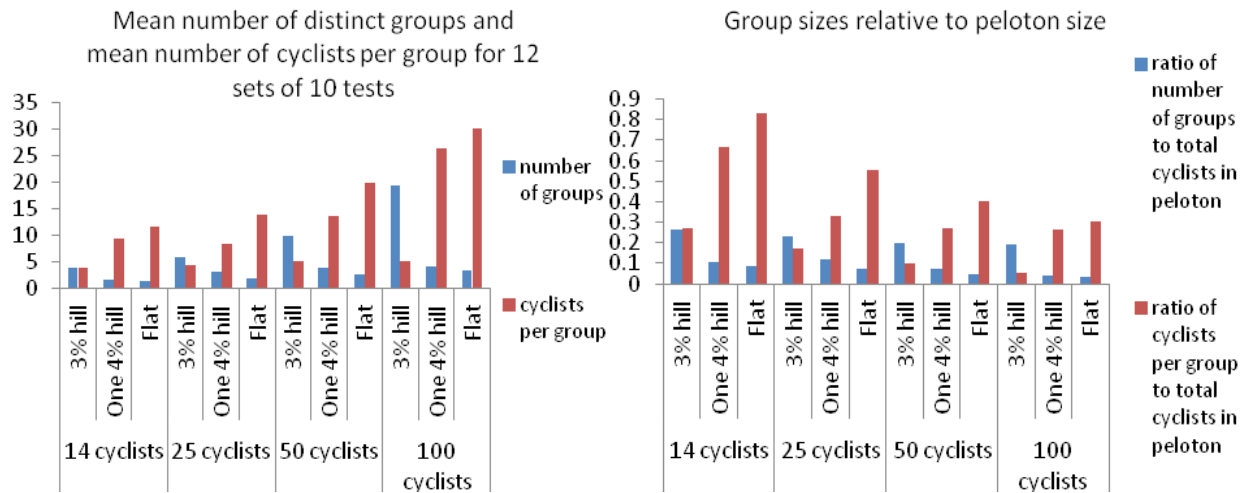


Figure 5a. Mean number of distinct groups and number of cyclists per group, per test. Generally, simulated pelotons tended to divide most frequently when high power outputs were sustained (“3% hill”), as expected. Pelotons tended to split less frequently on flat courses and when a single extended high output period was introduced (“One 4% hill”). **5b.** Ratios of group size to total peloton size indicate that smaller pelotons on flat courses produce greatest cohesion; introducing a single extended high output period produced somewhat dropping cohesion (increasing division), while continuous high output (“3% hill”) produced high peloton division.

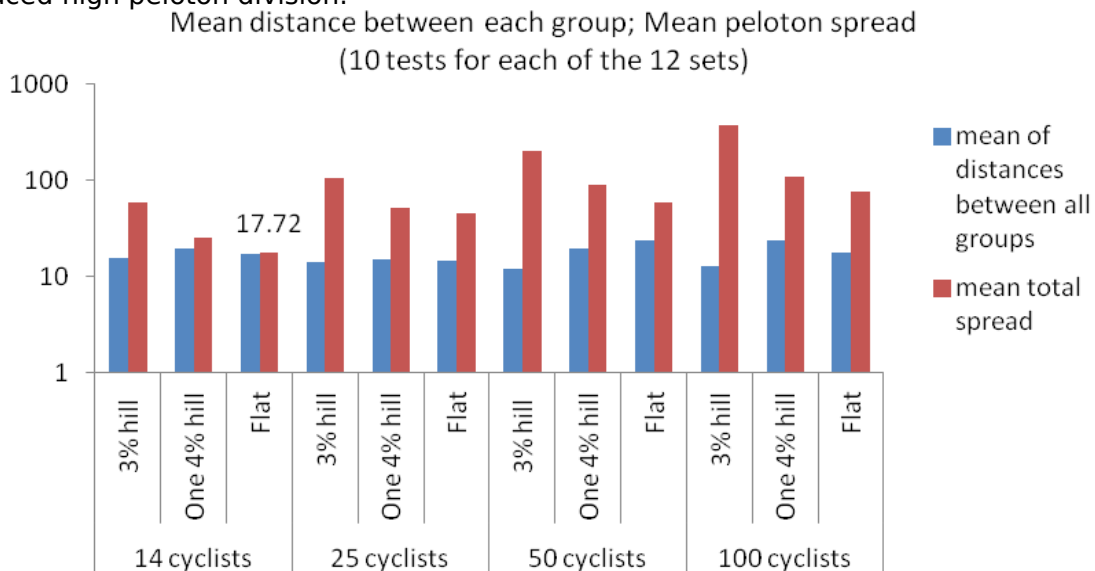


Figure 6. Log plot of mean distance between all groups for each set of tests and total group spread (distance between first and last simulated cyclists). Spread for 14 cyclists on the flat course is shown in comparison with the actual Points Race spread (~63m). Log plotting is used to compress scale.

Means distances between groups (10 runs per test variable)

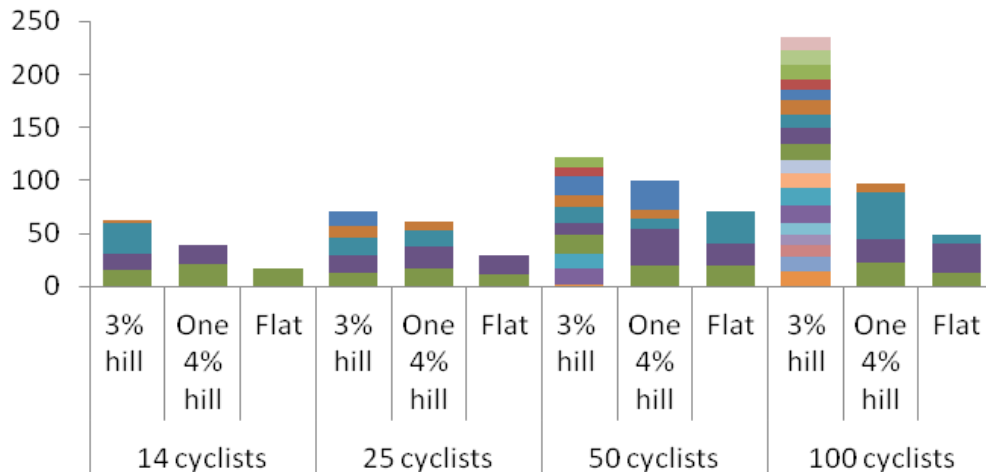


Figure 7. Distances between each group, indicated by coloured blocks. The number of groups equals $n+1$, where n is the number of coloured blocks (this does not include single cyclists between groups, which were not counted).

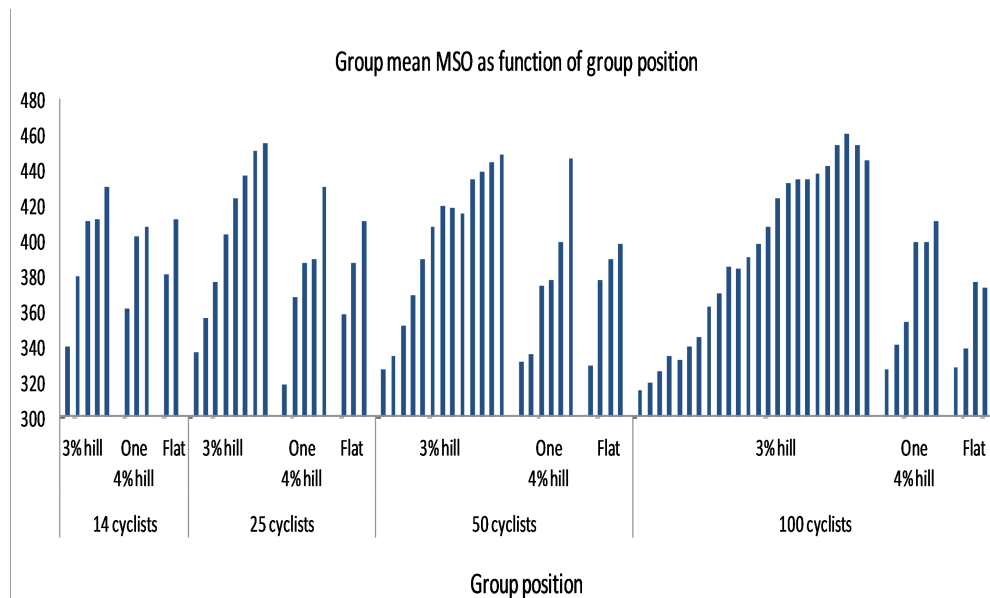


Figure 8. Mean Group *MSO* ascends in correspondence to group position. Groups farthest from the front (to the left) exhibit lower mean *MSO*.

Simulation results support the intuitive prediction that groups positioned behind the leading group tend to contain riders with lower mean *MSO*, corresponding to group order, as shown in Figure 8. This trend is consistent across experimental groups. Cyclists' finishing positions in Figure 1 can thus be compared with simulation results and, particularly for mountainous terrain (lower left), extrapolated to correspond with relative cyclist fitness.

The model is less persuasive in terms of its peloton stretch. In the Points Race, peloton stretch at the finish was observed to be approximately 63m, compared to a mean stretch of approximately 18m over 10 tests, as shown in Figure 6.

This difference may be partly explained by cyclists “giving up” at the end of the race, decelerating to a speed corresponding to an output well below *MSO*, thereby stretching the peloton more than if the race had continued such that cyclists maintained power output at *MSO* (as was the case for the simulation). Such resignation among riders at the finish of a race is common when only a few of the top positions are contested in earnest during a final all-out sprint, resulting in anomalous stretching at the end of the race that would not occur during vast majority of the race as all riders seek to maintain contact with the peloton. Additionally, this difference in simulation versus actual stretch data may be further explained by accumulated fatigue at the finish that was not captured in the simulation.

Conversely, simulation parameters may also be responsible for the truncated simulation end-state peloton stretch. This suggests that the balance between CS parameters, speed and deceleration parameters could be further fine-tuned to match the real world data. Moreover, the balance among the parameters, while shown to be set with reasonable accuracy for the 14 cyclists in the Points Race, may become less realistic for group sizes substantially different than 14.

The truncated simulation stretch suggests the final distances between simulated groups, as shown in Figure 7, may not precisely reflect real-world separations between groups. However, this does not substantially undermine the integrity of the model in demonstrating the group sorting dynamic, which is robust across a variety of experimental parameters. Moreover, the simulation stretch (lower image, Figure 3) which shows short term high stretch, followed by increased peloton density, reflects with reasonable accuracy the oscillation dynamics of the actual Points Race, in which the peloton remained generally cohesive for the whole race.

Conclusions

Overall, the agreement between simulated and actual race profiles supports the viability of the model as evidence of actual peloton dynamics. The model is reasonably accurate in terms of its deceleration parameter and the resulting oscillation between stretching (decreased density) (as speeds temporarily reach speed above that corresponding to *MSO*), and increased density (as speeds relax when cyclists in a given group are generally below their individual *MSO*). The model well supports the supposition that, at high relative outputs, sub-groups form that are composed of cyclists with lower mean *MSO*, in correspondence with sub-dominant group position.

One weakness of the model is that simulated bicycle peloton dynamics may not be accurate when the average speed is well below that corresponding to *MSO*, yet the peloton is in a high density state. For example, an observed convective phase is thought to occur within such a range of parameters, whereby cyclists freely pass others in general movement toward the front around the peloton periphery [11, 14]. The present model has not been tested for the emergence of this phase dynamic, although a model of this phase does exist [14]. Elements of a backwards convection, as discussed in [11] do appear to correspond with the deceleration phase, however, measurements of

long-term equilibrium backwards-convective states were not attempted here. Further experiments may be run to test for the presence of this dynamic.

Empirical data that includes VO_{2max} values for cyclists may be compared with the simulation results here. Similar measurements of aerobic capacity, speed, and coupling parameters may be sought for other biological collectives. We predict that by driving groups to reach power outputs near the maximally sustainable level, group sorting will occur in a manner similar to that observed for bicycle pelotons. Empirical studies for other such biological collectives will be needed to test this prediction, as well as to inform the selection of model parameters in order to test whether the model produces the proposed dynamics.

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Appendix

Power:

$$P = C_m V \left(C_d A \frac{\rho}{2} (V + W)^2 + F_{rg} + V C_r V n \right)$$

(8)

Speed:

In order to solve this Power equation for Velocity V , we write it in the implicit form

$$V^3 + 2V^2\left(W + \frac{C_{rVn}}{C_dA\rho}\right) + V\left(W^2 + \frac{2F_{rg}}{C_dA\rho}\right) - \frac{2P}{C_m C_d A \rho} = 0 \quad (9)$$

so we can use the cardanic formulae to obtain the solutions:

If $a^2 + b^3 \geq 0$:

$$V = \sqrt[3]{a + \sqrt{a^2 + b^3}} + \sqrt[3]{a - \sqrt{a^2 + b^3}} - \frac{2}{3}\left(W + \frac{C_{rVn}}{C_dA\rho}\right) \quad (10)$$

If $a^2 + b^3 < 0$ (casus irreducibilis; in case of sufficient downhill slope or tailwind speed):

$$V = 2\sqrt{-b} \cos\left(\frac{1}{3} \arccos \frac{a}{\sqrt{-b^3}}\right) - \frac{2}{3}\left(W + \frac{C_{rVn}}{C_dA\rho}\right) \quad (11)$$

with

$$a = \frac{W^3 - C_{rVn}^3}{27} - \frac{W(5WC_{rVn} + \frac{8C_{rVn}^2}{C_dA\rho} - 6F_{rg})}{9C_dA\rho} + \frac{2F_{rg}C_{rVn}}{3(C_dA\rho)^2} + \frac{P}{C_m C_d A \rho} \quad (12)$$

and

$$b = \frac{2}{9C_dA\rho} \left(3F_{rg} - 4WC_{rVn} - W^2 C_d A \frac{\rho}{2} - \frac{2C_{rVn}}{C_dA\rho}\right) \quad (13)$$

- P** Rider's power
- V** Velocity of the bicycle
- W** Wind speed
- H_{nn}** Height above sea level (influences air density)
- T** Air temperature, in ° Kelvin (influences air density)
- grade** Inclination (grade) of road, in percent
- β** ("beta") Inclination angle, = arctan(grade/100)
- m_{bike}** Mass of the bicycle (influences rolling friction, slope pulling force, and normal force)
- m_{rider}** Mass of the rider (influences rolling friction, slope pulling force, and the rider's frontal area via body volume)
- C_d** Air drag coefficient
- A** Total frontal area (bicycle + rider)
- C_r** Rolling resistance coefficient
- C_{rV}** Coefficient for velocity-dependent dynamic rolling resistance, here approximated with 0.1
- C_{rVn}** Coefficient for the dynamic rolling resistance, normalized to road inclination; $C_{rVn} = C_{rV} \cdot \cos(\beta)$
- C_m** Coefficient for power transmission losses and losses due to tire slippage (the latter can be heard while pedaling powerfully at low speeds)
- ρ** ("rho") Air density
- ρ_o** Air density on sea level at 0° Celsius (32°F)
- p_o** Air pressure on sea level at 0° Celsius (32°F)
- g** Gravitational acceleration

F_{rg} Rolling friction (normalized on inclined plane) plus slope pulling force on inclined plane