Accepted manuscript
Fujii, Y. and Alam, AKM B. (2026), Case studies on time-trial pacing strategies in cycling: Incorporating the peak power-time curve and acceleration, International Journal of Sports Science & Coaching, https://doi.org/10.1177/17479541261425368.

Case Studies on Time-Trial Pacing Strategies in Cycling: Incorporating the Peak Power–Time Curve and Acceleration

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ABSTRACT

This study examines optimal pacing strategies for cycling time trials by considering both the peak power–time curve and acceleration. We developed a computational model to simulate exertion and speed based on each cyclist's individual power characteristics. Two amateur cyclists (YF and AT) tested the proposed strategies during the Rumoi Hill Climb Time Trial (2.3 km), and their performances were compared with those from previous races using constant-power or free-ride strategies. The optimized two-level pacing reduced simulated finish times by 6.8 s (2.1%) and 8.2 s (2.5%), while actual improvements of 2.6 s (0.8%) and 7.9 s (2.4%) were observed. The model further suggested a potential 2.3% reduction in finish time for the 2025 UCI World Championships Women's Individual Time Trial (31.2 km) using a six-level pacing strategy based on YF's power profile. In addition, the proposed pacing strategy appeared potentially effective even in a mass-start hill climb: a solo effort using a constant-power strategy achieved an 8.8% improvement over the previous year, although this was based on a single case (*n* = 1). These results indicate that simplified and practical pacing strategies derived from power–time relationships can meaningfully enhance performance, including under real race conditions.

Keywords

Cycling time trial; pacing strategy; peak power–time curve; acceleration; performance optimization

1. Introduction

Power management is critical in cycling time trials. Variable power pacing—raising power on climbs or into headwinds and reducing it on descents or with tailwinds—has been shown to shorten race times.[1–6] Most previous studies, however, have been primarily theoretical. Cangley et al. (2011) validated the uphill–downhill strategy through field experiments,[4] but the observed performance gains were smaller than predicted because some riders were unable to sustain the required higher power outputs on climbs. Increasing power on climbs or into headwinds therefore entails a risk of premature fatigue. Consequently, simulations of pacing strategies must account for the relationship between power output and sustainable duration. Gordon (2005) simulated 40-km time trials using exertion derived from the peak power–time curve,[7] and found that variable pacing was ineffective on a single climb but beneficial on repeated 1-km climbs and descents, whereas wind-based power variations provided little advantage.

Although acceleration is crucial in short time trials, it has been overlooked in some previous studies.[1–3,7] Dahmen et al. (2012) optimized power profiles for constant-gradient and uneven uphill courses by incorporating both exertion and acceleration.[8] They reported that the optimized power profile reduced the simulated finish time from 849 s in a free ride to 834 s on a 3600-m course in a simulator. However, they did not present results from actual rides performed using the optimized profile. Building on these findings, we developed a computational code to simulate cycling time-trial performance while incorporating both exertion derived from the peak power–time curve and the effects of acceleration.[9] With the aim of identifying simple and practical pacing strategies that cyclists can realistically adopt, we propose basic guidelines for time-trial races.

In this paper, we apply our computational code to propose optimal pacing strategies for a specific race, with a focus on amateur cyclists who can realistically follow them. As a case study, the results are compared with previous race outcomes obtained without optimal pacing, and the effectiveness of the proposed strategies is discussed. With the exception of Cangley et al. (2011),[4] most of the aforementioned studies remain theoretical; therefore, the present study is valuable in validating pacing strategies based not only on simulations but also on actual race results. Moreover, unlike Cangley et al. (2011),[4] we explicitly incorporate the peak power–time curve. Although Dahmen et al. (2012)[8] demonstrated precisely optimized pacing profiles, such profiles are too complex to memorize and difficult for cyclists to implement in practice. By contrast, we simplify the course and propose only two discrete power levels, which can be easily remembered and realistically followed.

Next, we apply the method to the women's individual time-trial course of the 2025 UCI World Championships as a case study of a long international race, although this analysis remains purely simulation-based. Finally, we demonstrate that the proposed pacing strategy is potentially effective even in a mass-start hill-climb race, using actual race data.

2. Methods

2.1 Estimation of peak power-time parameters

For the relationship between power P and maximum duration t_c, the 3-parameter critical power model proposed by Morton (1966)[10] was adopted:

$$t_C = \mathrm{AWC}\left(\frac{1}{P - P_C} - \frac{1}{P_{max} - P_C}\right) \quad (1)$$

where AWC is the anaerobic work capacity, P_C is the critical power (the asymptotic power for infinite duration), and P_{max} is the maximum power (where t_C becomes zero).

The parameters AWC, P_{max} and P_C in Eq. (1) can be calculated using at least three, preferably four or more, average power-maximum duration data points. In this study, peak power values were collected from participants at 30 s, 1 min, 2 min, 5 min, and 20 min, and calculations were performed using the solver function in Microsoft Excel.

Cumulative anaerobic work AW for varying power can be calculated as:

$$\mathrm{AW} = \sum_{i=1}^{n} \frac{(P_i - P_C)(P_{max} - P_C)}{(P_{max} - P_i)} \Delta t \quad (2)$$

for a data series at t_i, ($i = 1, 2, ..., n$), with a time interval of Δt. Exertion E is defined as

$$E = \frac{\mathrm{AW}}{\mathrm{AWC}} \quad (3)$$

(Gordon, 2005).[7] It is assumed that the rider can no longer sustain the required power level when $E = 1$. Exertion immediately reaches 1 if P reaches P_{max}. Recovery occurs when $P < P_C$, leading to a decrease in AW and E. The functional form of exertion recovery should be investigated further in future studies.

2.2 Estimation of best power levels for course sections

Acceleration is calculated from pedaling power, rider and bicycle mass, wheel inertia, aerodynamic drag, rolling resistance, and the component of gravity along the slope. Infinitesimal exertion is computed from the applied power and the peak power–time curve. Speed, distance, and exertion are then obtained using a sequential time-integration method. Details of the calculation algorithm are provided in Fujii and Alam (2025),[9] except that horizontal distance is used instead of inclined distance for presenting the results; the appropriate conversion is, of course, implemented in the calculation code. Wind effects are neglected, and standard atmospheric conditions—an air pressure of 1013 hPa, an air temperature of 298 K, and a relative humidity of 50%—are assumed to determine air density, which affects aerodynamic drag. This simplification is adopted because these environmental factors are difficult to predict in advance. Fortunately, none of the races analyzed were conducted under extreme weather conditions. Nevertheless, incorporating a range of weather conditions into pacing calculations and selecting the most representative scenario, or adjusting to actual race conditions, would be preferable in future studies.

We first apply a constant-power strategy, in which a fixed power level is assumed and the resulting exertion is calculated. The maximum sustainable power is determined by requiring that exertion does not exceed unity, using a trial-and-error procedure with a time step of 0.01 s and a power resolution of 1 W. Next, we examine a variable-power strategy, in which power is increased on uphill sections and decreased on flat and downhill sections. The set of power levels that minimizes the finish time while maintaining exertion below unity is identified, again with a resolution of 1 W.

A resolution of 1 W is sufficiently precise given the accuracy of commercially available power meters, day-to-day variations in cyclists' physical condition, and the limited ability of humans to control output power. With this resolution and the simplified course segmentation adopted here, manual optimization is feasible. The basic principle is to maximize power such that exertion does not exceed unity by the end of the section preceding the finish or a downhill segment. Conversely, for downhill or flat sections preceding an uphill segment, the highest power at which exertion recovers to zero is sought. Automatic optimization would be required if the course were divided into numerous sections and a more complex optimal pacing profile were considered; however, such an approach is beyond the scope of this paper.

2.3 Validation of the strategy

We proposed the pacing strategies to amateur cyclists, who attempted to follow them during actual races. Route, distance, power, speed, cadence, heart rate, and temperature were recorded using commercially available devices, including heart-rate monitors, speed sensors, and power meters, with all data logged on GPS cycle computers. These measurements, together with finish times, were compared with both the simulated results and the finish times from the same races in previous years when the pacing strategies had not been applied.

3. Rumoi Hill Climb Time Trial

3.1 Cyclists and peak-power parameters

YF is a 63-year-old male (as of September 19, 2025) with more than 30 years of cycle racing experience. Because he generally trains below his peak strengths, the higher of his peak power levels measured in 2024 or 2025 was used to determine the peak-power parameters (Tables 1 and 2).

AT is a 61-year-old male (as of September 19, 2025) with 11 years of cycle racing experience. He typically trains at his peak strengths, and his most recent peak power levels and the corresponding peak-power parameters are listed in Tables 1 and 2. The 20-min peak power value was excluded from the parameter estimation because its inclusion resulted in an unrealistically high value of P_{max} (437 kW). This discrepancy is likely attributable to the peak power levels having been measured at different times under varying fitness conditions.

We acknowledge that the sample size in this study is limited. Rather than adopting a statistical approach with a large cohort, this paper focuses on detailed analyses of individual cyclists; a broader statistical investigation involving a larger number of participants should be conducted in future work. The diversity of the sample is also limited. However, inclusion of both male and female cyclists is not essential in the present context, because the primary difference between men and women in cycling time-trial performance lies in absolute power output rather than in pacing strategy itself.

Veteran cyclists were intentionally selected because they have followed similar training routines over many years and are able to prepare their physical condition for races through extensive experience. As a result, their performance is typically at a plateau or gradually declining. Under such conditions, any improvement in performance can be more confidently attributed to changes in pacing strategy. In contrast, for younger cyclists, elite athletes, or cyclists with lower and rapidly changing fitness levels, improvements in race performance are difficult to distinguish from gains due to increasing fitness.

3.2 The race and the optimal pacing strategies

The Rumoi Hill Climb Time Trial (https://rumoihcctt.jimdofree.com, accessed September 19, 2025; available only in Japanese) was held on June 29 in Rumoi, Japan. A key feature of this race is that the first 1.3 km is completely flat, whereas the final 1.0 km consists of an uphill section with an average gradient of 7.6% (Fig. 1). At the end of the flat section, a sharp corner may require braking. The event follows an individual time-trial format, with rankings determined by the combined finish time of two trials separated by approximately one hour.

For simulation purposes, the course was simplified as a 1.3 km flat segment followed by a 1.0 km uphill segment at a constant gradient of 7.6% (Fig. 1). A braking zone was assumed at the end of the flat segment, where pedaling ceases and speed is reduced to 28.8 km/h over a distance of 50 m.

The input parameters used in the simulations are summarized in Table 3. These parameters were not measured directly but were reasonably assumed, as materials and clothing can vary depending on conditions. For YF, a CdA value of 0.25 m^2 was assumed, corresponding to an aerodynamic position using clip-on time-trial bars, even on the uphill section. For AT, a CdA of 0.25 m^2 was assumed on the flat section and 0.30 m^2 on the uphill section, assuming a bracket position.

Gear ratio selection affects the starting sprint because the maximum pedaling force was assumed to equal the rider's body weight, although this effect is negligible over the entire race. It was further assumed that optimal gear ratios were used for the remainder of the course. The virtual mass m', derived from the wheels' moment of inertia I, is defined as:

$$m' = \frac{I}{r_W^2} \tag{4}$$

where r_W is the tire radius. The wheel-and-tire assembly was assumed to have half of its total mass concentrated at this radius.

The maximum sustainable power for the constant-power strategy and the corresponding simulated finish times are presented in Table 4. For the optimal pacing strategy, discrete power levels were assigned to each course section. Preliminary calculations showed that the shortest finish time was achieved by reducing power on the flat section such that exertion immediately after the braking zone was zero, while applying the maximum sustainable power on the uphill section. These optimal power levels were determined through a trial-and-error procedure (Table 4; Fig. 2a). As a result, the optimized pacing strategy reduced the simulated finish times by 6.8 s (2.1%) for YF and 8.2 s (2.5%) for AT compared with the constant-power strategy.

Previous race results are summarized in Table 5. AT performed a free ride in 2024, defined here as riding without a specific pacing strategy. During the free ride, output power was highest at the start and gradually decreased, except for slight increases at the beginning of the uphill section and near the finishing sprint (Fig. 3a). YF also performed a free ride in 2019. In 2024, he estimated the maximum sustainable power corresponding to a 5-min effort from his peak power–time curve with a resolution of 10 W and adopted an approximate constant-power strategy. His output power remained nearly constant except for the start sprint (Fig. 3b), resulting in a finish-time improvement of 12.5 s (3.7%) compared with his 2019 free ride.

It should be noted that pacing strategies resembling free rides—characterized by maximal power at the start followed by a gradual decrease toward an all-out effort at the finish—are effective for flat time-trial courses of 1 km or shorter.[9,11]

3.3 Time-trial race results and comparison with past performances

The participants attempted to follow the proposed power profiles during the 2025 race and were largely successful, although slightly excessive power was produced at the start and at the beginning of the uphill section (Fig. 2a). This led to higher exertion in the early stage of the race and a subsequent reduction in power over the remainder of the climb. Nevertheless, YF improved his finish time by 2.6 s (0.8%) compared with the constant-power strategy used in 2024, and AT reduced his finish time by 7.9 s (2.4%) compared with his free ride in 2024.

4 UCI World Championships 2025 Women's Individual Time Trial (simulation only)

The race was held in 2025 in Kigali, Rwanda. The course length was 31.2 km and featured three uphill sections with a total elevation gain of 460 m (https://www.uci.org, accessed October 1, 2025). The winner's finish time was 2589.34 s, corresponding to an average speed of 43.38 km/h. The course profile provided on the UCI website was examined and simplified into six sections (Fig. 4a). An aerodynamic position was assumed throughout the race.

Although lower air density may reduce aerodynamic drag and reduced oxygen availability may decrease power output, the same atmospheric conditions and power parameters as in the previous analysis were assumed for simplicity. Deeper wheels were assumed, and the bicycle and virtual wheel masses were increased to 8.5 kg and 1.20 kg, respectively. A slightly smaller CdA of 0.23 m^2 was also assumed. Because personal power data for the participants were not available, YF's power data were used. While the power profiles of elite professional cyclists would likely yield faster finish times and potentially different optimal strategies, YF's power data provide a representative reference level for this simulation.

The maximum sustainable constant power for YF was determined to be 246 W (Fig. 4b), resulting in a simulated finish time of 3132.4 s.

Optimal pacing was then investigated (Fig. 4b). The key principle is that exertion should be reduced to zero before entering each uphill section in order to maximize climbing power (Fig. 4d). To achieve this, power on the initial flat section was set close to the critical power, and power on downhill sections was reduced so that exertion recovered to zero before the subsequent uphill. As a result, simulated downhill speeds were lower than those obtained with the constant-power strategy (Fig. 4c), whereas uphill speeds were slightly higher. Overall, the optimized pacing strategy reduced the simulated finish time to 3059.0 s, corresponding to an improvement of 73 s (2.3%) relative to the constant-power strategy.

5 Mass-start hill-climb race

The 32nd Mount Moiwa Hill Climb was held on July 13, 2025, in Sapporo, Japan (https://sapporo-cf.jp/result/result.html, accessed October 3, 2025; available only in Japanese). The course of this mass-start hill climb was modeled as a 4.0 km uphill with a constant gradient of 8.3% (Fig. 5). The same parameters as those listed in Table 3 were used, except for a CdA of 0.30 m^2 corresponding to a bracket position and smaller values of the bicycle mass m and virtual wheel mass m' (7.5 kg and 0.9 kg, respectively), representing lightweight wheels. The maximum sustainable constant power—which is equivalent to the optimal pacing strategy because of the uniform slope—was calculated to be 255 W, yielding a simulated finish time of 992.19 s for YF.

Because this was a mass-start race, riders could theoretically benefit from drafting, particularly immediately after the start. However, YF maintained near-optimal power shortly after the start (Fig. 5b) and rode solo for the remainder of the race, gaining virtually no drafting advantage. Nevertheless, he recorded a personal best finish time of 1000.66 s, only 0.8% slower than the simulated result. By contrast, in the previous year, he produced high power at the start in order to follow the leading group and obtain a drafting benefit, followed by a subsequent reduction in power (Fig. 5b). His official finish time in that race was 1088.50 s, which is 88 s (8.8%) slower than the solo effort with optimal pacing achieved in 2025.

6. Discussion

Across the cases examined, the largest discrepancy between simulated and actual finish times was −3.0%. The primary objective of the simulation is not to predict finish times with high precision, but to identify optimal pacing strategies. Nevertheless, the relatively small deviations indicate that the simplified course profiles, together with the estimated and assumed parameters and environmental conditions, are reasonably adequate. More importantly, the proposed optimal pacing strategies successfully reduced actual finish times by 0.8–8.8%. Such improvements are typically difficult to achieve for veteran cyclists, whose power output generally declines with age, without the aid of a structured pacing strategy. Their training routines are usually similar from year to year, and their functional threshold power (FTP[12]) tends to decrease gradually; for example, YF's FTP declined from 248 W in 2023 to 243 W in 2024 and 236 W in 2025. Wind conditions during the races were weak (Table 5), suggesting that environmental variability played a minor role in the observed performance changes.

An aerodynamic riding position was assumed for YF even on the uphill section of the Rumoi course, and he was able to maintain this position during the actual race. In the simulations, if a bracket position had been adopted on the uphill, the optimal power for the flat section remained unchanged, whereas the optimal power for the uphill section decreased to 302 W. This resulted in a finish time that was 2.80 s (0.9%) slower. This comparison demonstrates that the proposed simulation framework can be applied to various practical evaluations, including rider position and trade-offs between aerodynamic benefits and additional mass from components, helmets, or other equipment.

For the UCI World Championships 2025 Women's Individual Time Trial, the simulation suggests that if the cyclist who finished 8th had adopted a constant-power strategy, the optimized pacing strategy could have improved her result to a 2nd-place finish. If her actual ride had resembled a free-ride strategy, an even larger improvement would be expected. Although this analysis is purely hypothetical, it highlights the potential impact of pacing optimization even at the highest competitive level.

For the Mount Moiwa Hill Climb, similar to the Rumoi case, the results indicate that—considering YF's age and extensive racing experience—achieving such a performance in 2025 would not have been possible without the aid of an optimal pacing strategy, even when foregoing the aerodynamic benefits of riding in a group.

7. Conclusion

Optimal pacing strategies for cycling time trials were investigated using a computational code developed by the authors that incorporates individual peak power–time curves and acceleration. The finish times of two amateur cyclists in the Rumoi Hill Climb Time Trial—a 2.3 km race consisting of a 1.3 km flat section followed by a 1.0 km uphill with a total elevation gain of 76 m—were compared with those obtained using constant-power strategies or previous free rides. Despite the simplified course representation and uncertainties in the input parameters, the optimal pacing strategy produced meaningful improvements in actual finish times.

Optimal pacing was also examined through simulation for the 2025 UCI World Championships Women's Individual Time Trial (31.2 km, 460 m total elevation) using YF's individual power data. The results indicated that the optimal pacing strategy could reduce the finish time by 73 s (2.3%) compared with a constant-power strategy. Although this analysis is purely computational, it suggests that optimal pacing may be effective even for long time trials featuring mixed flat, uphill, and downhill sections.

The effectiveness of the proposed pacing strategy was further explored in a mass-start hill-climb race involving YF. The course was modeled as a uniform slope, and the maximum sustainable power required to reach the finish was determined using the developed code. YF maintained near-optimal power from shortly after the start without relying on drafting and recorded a finish time that was 88 s (8.8%) faster than his result in the previous year, when he initially followed the group and subsequently reduced power. Although only a single case is presented, this result suggests that optimal pacing may also be effective in mass-start hill-climb races, even though in such uniform-slope conditions it is equivalent to a constant-power strategy.

Overall, the findings indicate that optimal pacing strategies may also benefit solo breakaways or chasing efforts in road races. The developed computational framework can be used not only to design practical pacing strategies but also to evaluate trade-offs between aerodynamic equipment, bicycle mass, and required gear ratios based on simulated speeds. Future work will focus on accumulating data from a broader range of races and participants in order to statistically validate the effectiveness and generality of the proposed strategies.

Ethical considerations

This study used performance data from two cyclists, including the author (YF) and a volunteer participant (AT). Although the data could potentially be linked to individual identities through publicly available race results, both participants provided written informed consent for the use of their data in this study. As the study involved only non-interventional analysis of performance data from consenting adults, institutional review board (IRB) approval was not required.

Consent to participate

All participants were fully informed about the purpose of the study and agreed to the use of their data.

Consent for publication

All participants provided consent for the publication of this study.

Declaration of conflicting interest

The authors declare that they have no competing interests.

Funding statement

This research received no external funding.

Data availability

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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Table 1 Peak power levels.

Duration (s)	Peak power (W)	
	YF	AT
30	482	566
60	393	417
120	351	363
300	282	292
1200	253	(267)

Table 2 Peak power parameters.

Parameters	YF	AT
AWC (J·s)	12604.3	17648.8
P_C (W)	242.6	238.3
P_{max} (W)	1046.0	864.8

Table 3 Mechanical parameters. M: mass of the cyclist, m: mass of the bicycle, m': virtual mass of the wheels. C_R: coefficient of rolling resistance, L: crank length, r_w: tire radius, R_G: gear ratio.

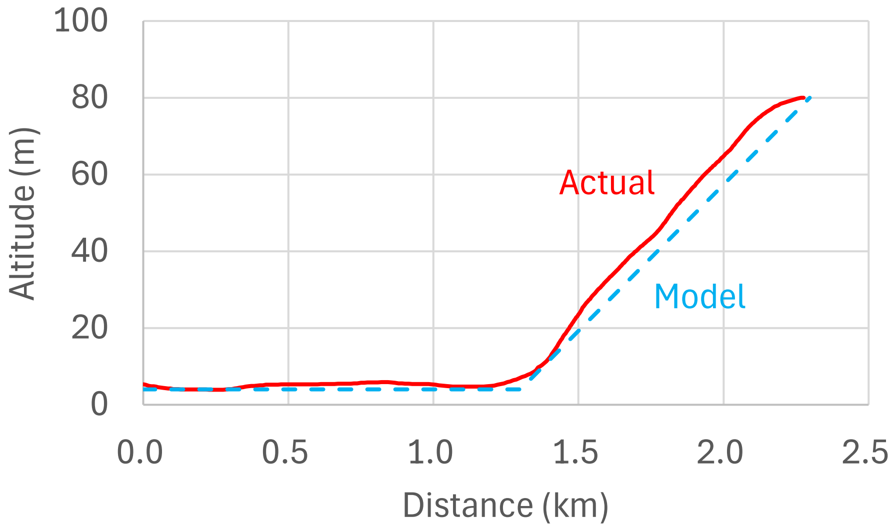
Parameters	YF	AT
M (kg)	62	66
m (kg)	8.2	7.8
m' (kg)	1.05	1.15
C_R	0.005	0.005
L (m)	0.17	0.17
r_w (m)	0.334	0.334
R_G (t/t)	53/19	53/19

Table 4 Assumed pacing and simulated finish time.

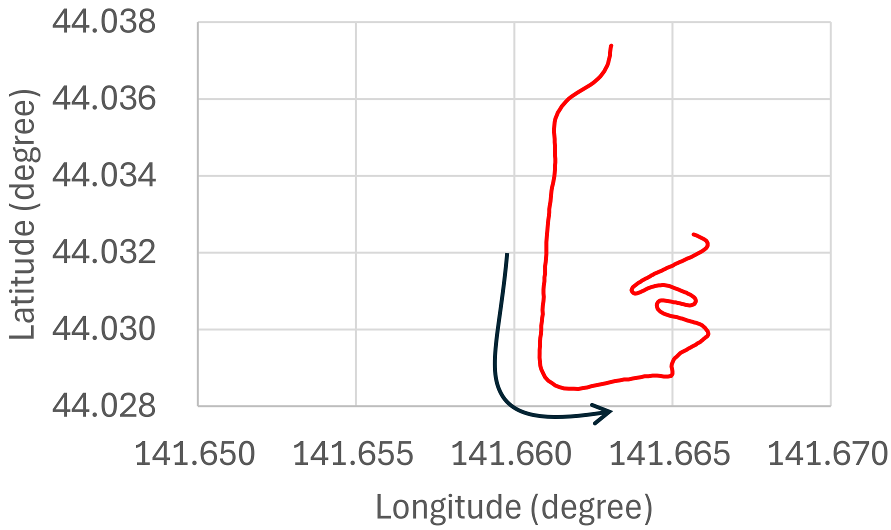
Parameters	YF	AT
Constant power strategy		
Power (W)	282	290
Finish time (s)	326.38	330.68
Average power (W)	280.8	288.8
Optimal pacing		
Power for flat section (W)	251	246
Power for uphill section (W)	302	317
Finish time (s)	319.63	322.49
Average power (W)	284.4	294.2

Table 5 Actual average finish time (s). PB: personal best.

Season	Finish time (s)	
	YF	AT
2025	326.61	322.31
	Optimal pacing	Optimal pacing
	PB placing	PB time
	Air temp. 22°C, RH: 74%, Wind: West 7.2 km/h	
2024	329.22	330.23
	Rough constant power	Free ride
	Air temp. 18°C, RH: 86%, Wind: North 6.1 km/h	
2019	341.72	
	Free ride	
	Air temp. 17°C, RH: 90%, Wind: ESE 9.7 km/h	

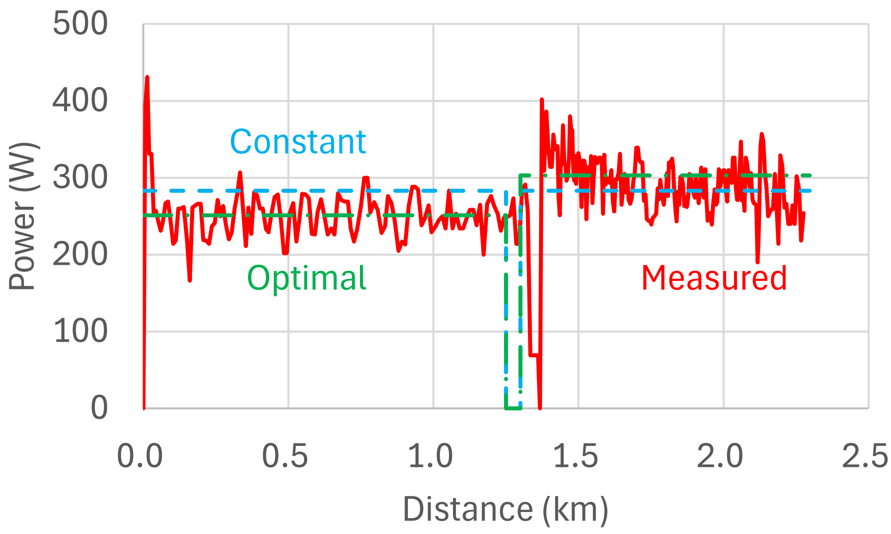


(a) Sectional view

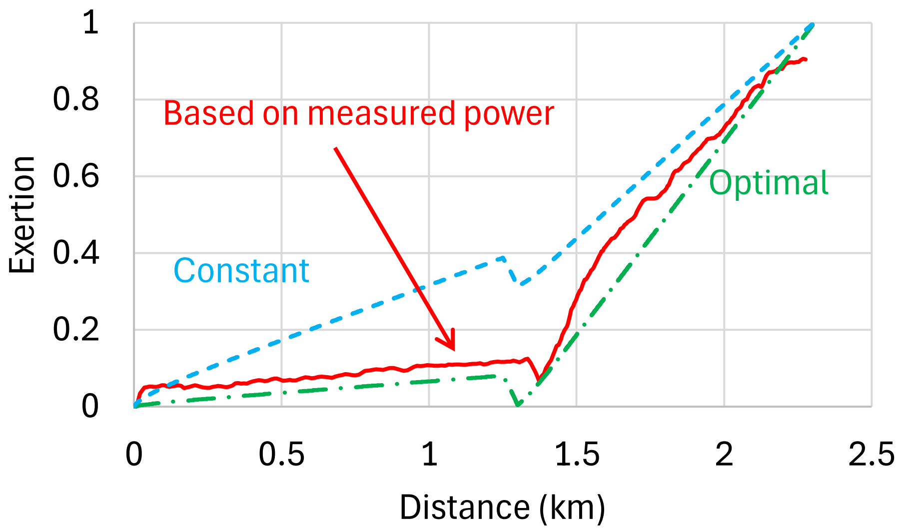


(b) Plan view

Fig. 1 Actual and simplified course profiles.

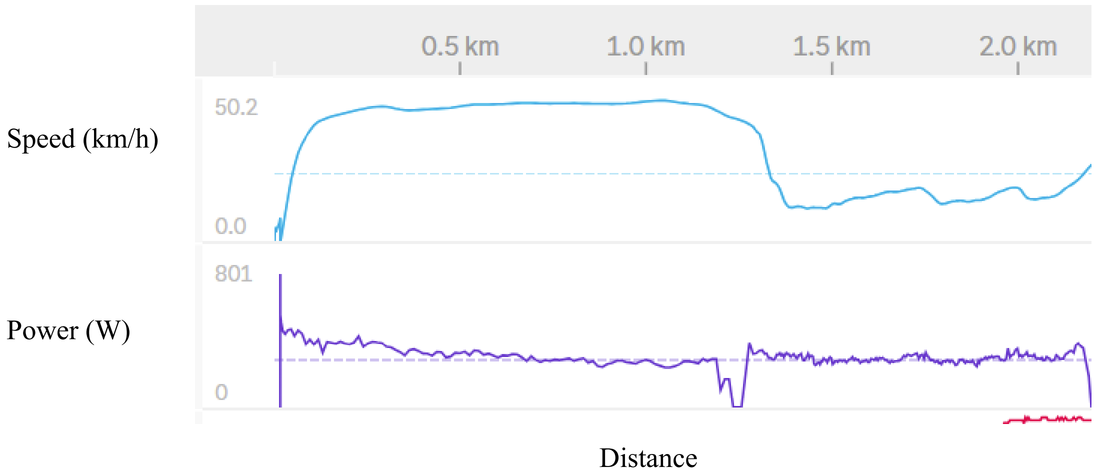


(a)

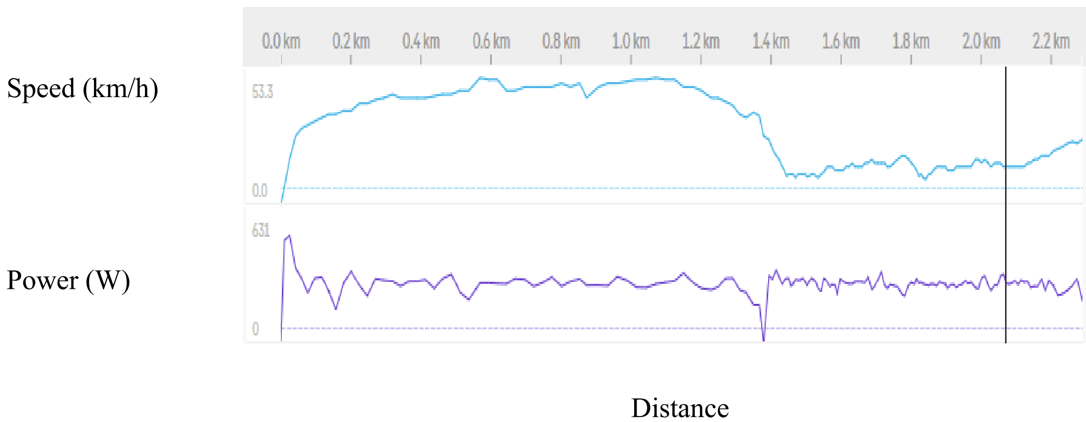


(b)

Fig. 2 (a) Proposed power and (b) simulated exertion for YF, compared with measured data from the first run.



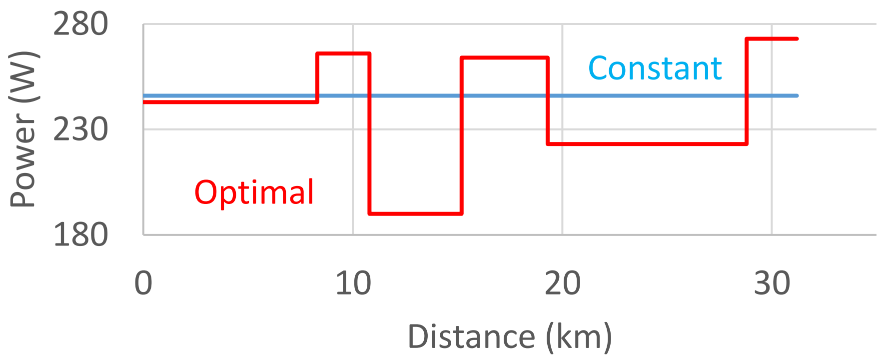
(a) Free ride



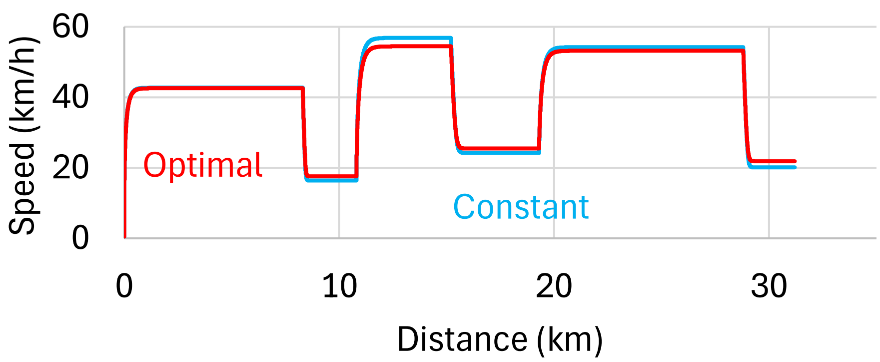
(b) Constant power strategy

Fig. 3 Typical power output for (a) free ride during the first run of AT in 2024 and (b) the constant power strategy during the second run of YF in 2024, as captured from STRAVA analysis window.

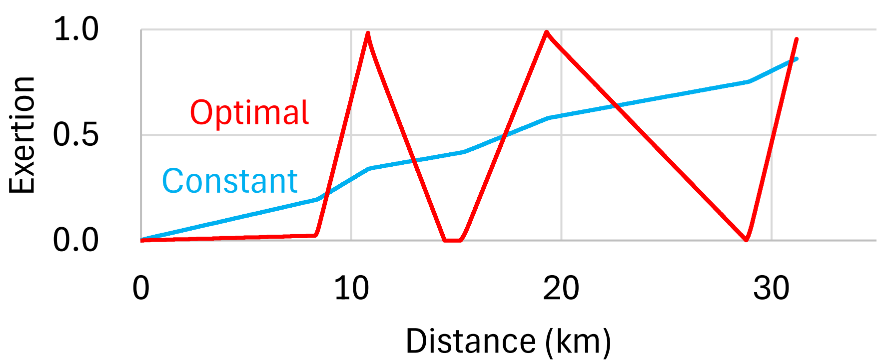
(a) Model



(b) Power profile

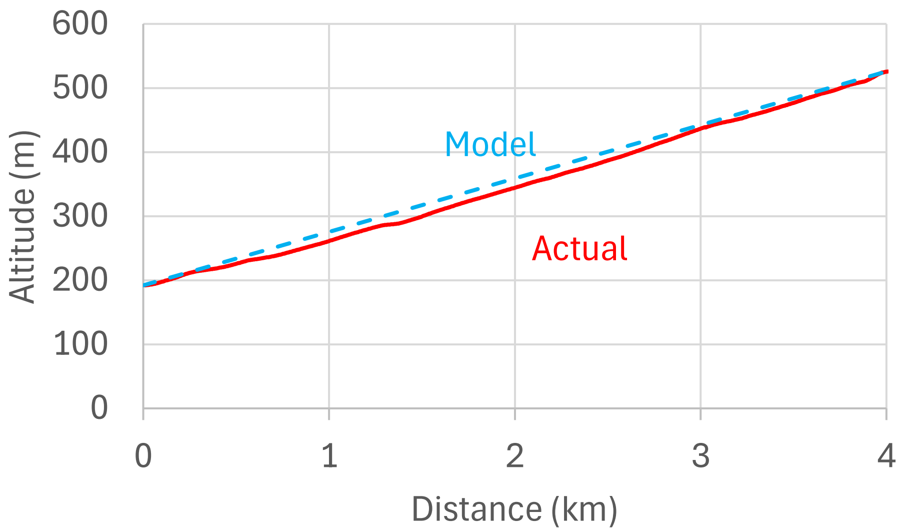


(c) Speed

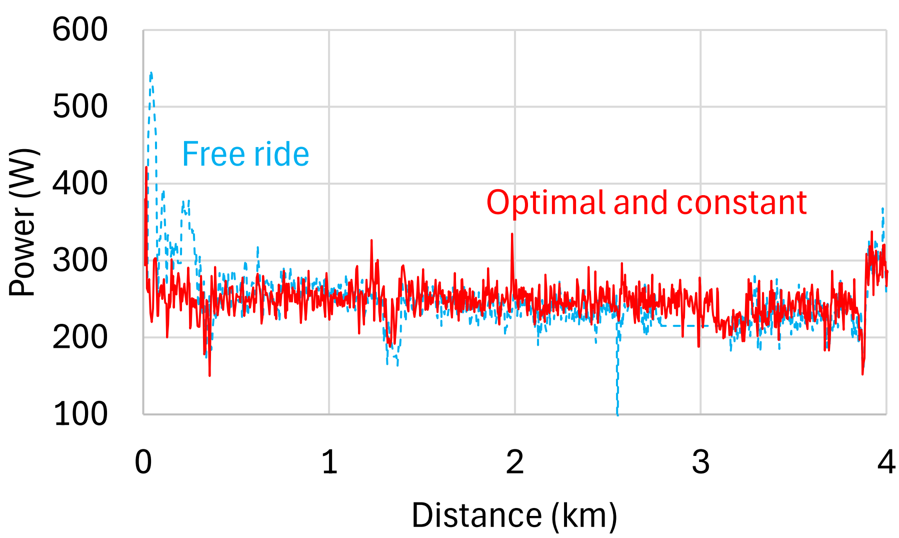


(d) Exertion

Fig. 4 Simulation results for the 2025 UCI World Championships Women's Individual Time Trial (ITT).



(a) Actual and modelled profile



(b) Measured power profiles.

Fig. 5 Mt. Moiwa hill-climb case.