Modeling in Road Cycling for Optimal Pacing Strategies: Theory vs. Practice

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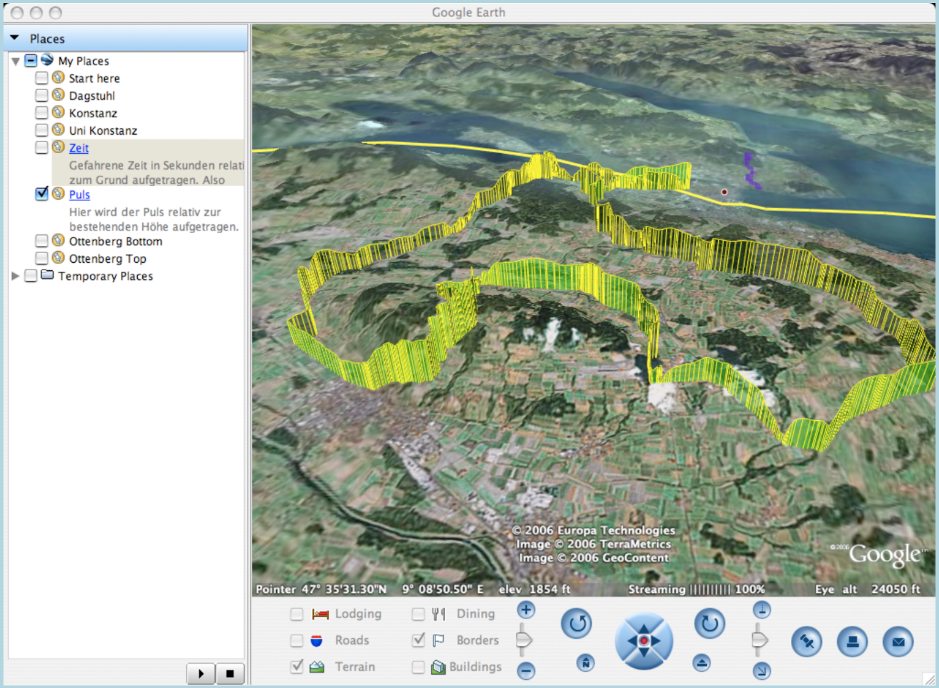
Bundesinstitut für Sportwissenschaft

DFG

Universität Konstanz

The Powerbike project @ University of Konstanz (since 2007)[1]



- Data acquisition, analysis, visualization, optimization of performance parameters
- Simulator: System controlled ergometer with video feedback
- Model-based computation of optimal pacing strategies
- Validation in field studies using an adaptive real-time feedback system

[1] https://www.mmsp.uni-konstanz.de/research/projects/powerbike/

Optimal pacing strategies

Definition

Given an uphill race track on a road (Strava segment) of length x_f, a *pacing strategy* for time trial is given by a function of travelled distance $0 \leq x \leq x_f$

$$F : [0, x_f] \to \mathbb{R}$$

where $F(x)$ denotes one of the following prescribed quantities at position x:

- power P
- speed v
- riding time t
- remaining anaerobic energy $0 \leq e_{an} \leq E_{an}$, ($e_{an} = W'$)

[1] Cangley, Passfield, Carter, and Bailey. The effect of variable gradients on pacing in cycling time-trials. Sports Med 32 (2011) 132–136.

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Best practice today to set the pacing strategy

- Ride slightly above your functional threshold power.
- When going uphill add 10–30 Watts of power, depending on slope[1].

The challenge of Science&Cycling

- Replace heuristic by a *feasible* model-based computational approach.
- Provide adaptive feedback technology to athlete while on the road.

[1] Cangley, Passfield, Carter, and Bailey. The effect of variable gradients on pacing in cycling time-trials. Sports Med 32 (2011) 132–136.

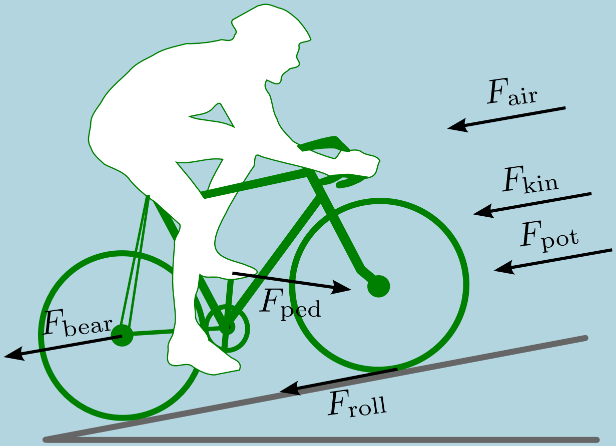
Roadmap

1. Implement a physical model of cycling (power $\longleftrightarrow$ speed)
2. Devise suitable models for fatigue, recovery, performance
3. Calibrate models using our simulator and field rides
4. Apply models for computing optimal personal pacing strategies
5. Lead riders on the road in real-time by feedback on a device on the handle bar
6. Adaptation of optimal strategy while riding
7. For riders/coaches: establish/revise rule set for optimal pacing

Physical model of cycling

Validation of a mathematical model for road cycling power[1]

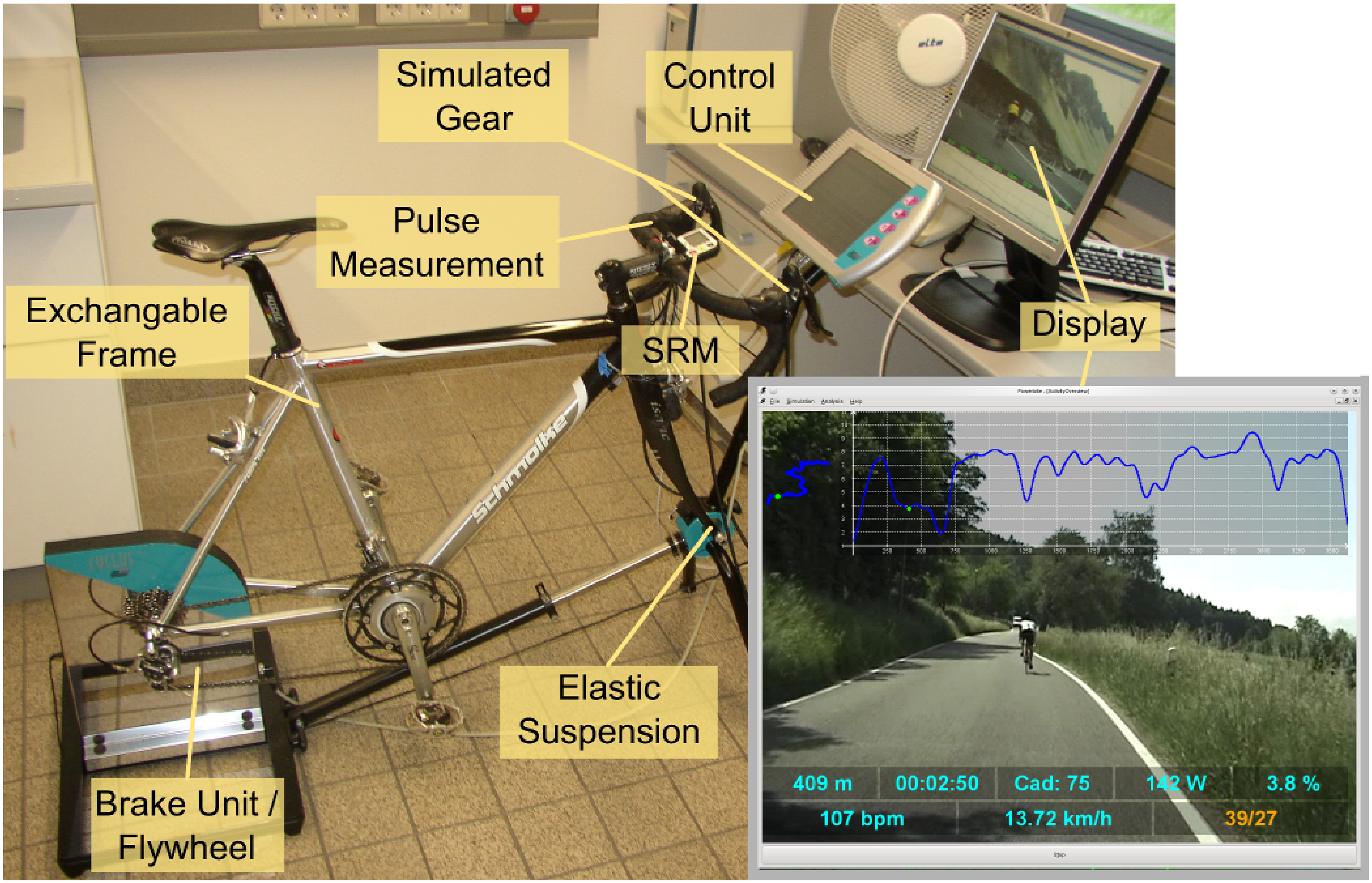
$$\underbrace{F_{\text{resist}} = mg\frac{\mathrm{d}h}{\mathrm{d}x}}_{F_{\text{pot}}} + \underbrace{\frac{1}{2}c_d\rho A\dot{x}^2}_{F_{\text{air}}} + \underbrace{\mu mg}_{F_{\text{roll}}} + \underbrace{(\beta_0 + \beta_1\dot{x})}_{F_{\text{bear}}} + \underbrace{\left(m + \frac{I_w}{r_w^2}\right)\ddot{x}}_{F_{\text{kin}}} = \frac{\eta}{\gamma}\frac{l_c}{r_w}F_{\text{ped}}$$



Cyclist and bicycle		Course and environment	
total mass (cyclist, bike)	m	friction factor	μ
wheel circumference	c_w	gravity factor	g
wheel radius	r_w	drag coefficient	c_d
wheel inertia	I_w	air density	ρ
cross-sectional area	A	length	L
length of crank	l_c	height	$h(x)$
bearing coefficient	β_0	chain efficiency	η
bearing coefficient	β_1		
mechanical gear ratio, bicycle	γ		

[1] Martin, Milliken, Cobb, McFadden, and Coggan. Validation of a mathematical model for road cycling power. Journal of Applied Biomechanics 14 (1998) 276–291.

Validated cycling simulator

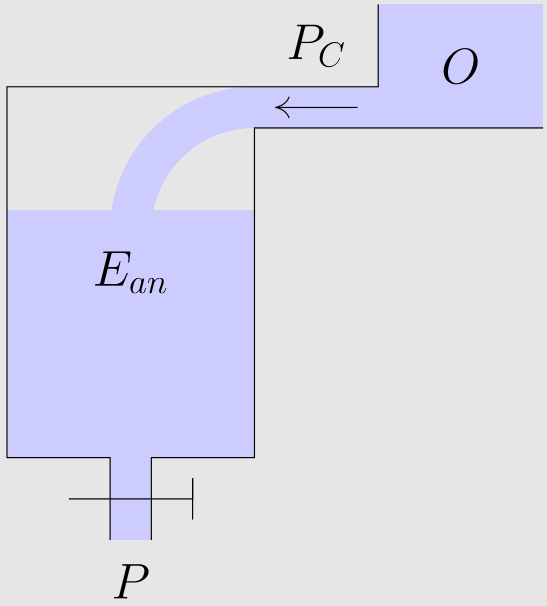


[1]Dahmen, Byshko, Saupe, Röder, and Mantler. Validation of a model and a simulator for road cycling on real tracks. Sports Engineering 14 (2011), 95–-110.

Physiological models I

Critical power, Monod & Scherrer (1965)

- 2-component hydraulic model
  - Critical power (P_c)
  - Anaerobic work capacity (E_{an})
- Works well for constant work rate tests.
- For variable power demand it overestimates recovery at subcritical power.

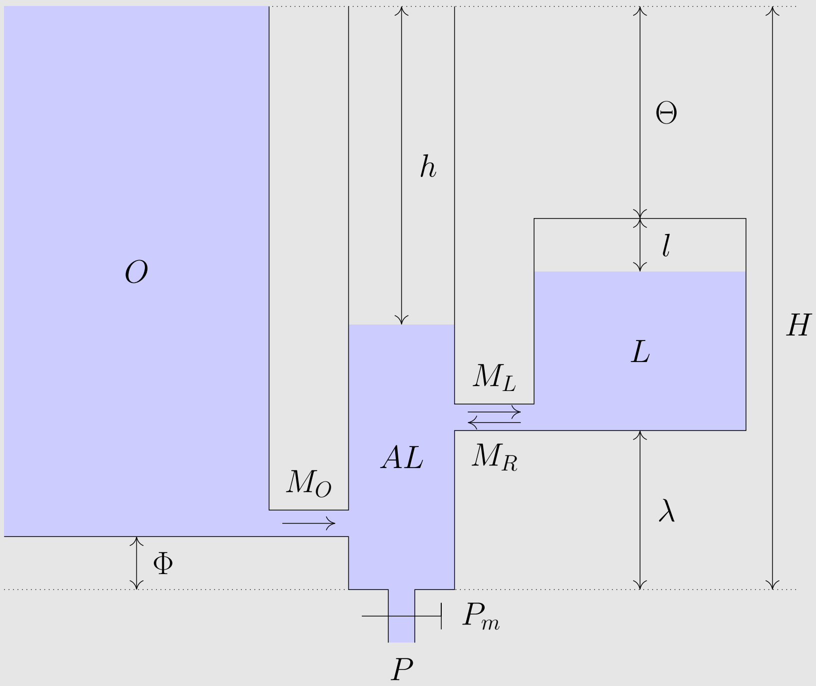


[1] Monod, H. & Scherrer, J. (1965). "The work capacity of a synergic muscular group". Ergonomics, 8(3):329–338.

Physiological models II

Margaria-Morton modell, Margaria (1976) & Morton[1] (2006)

- 3-component hydraulic model
- Models metabolic processes
- Many parameters, difficult to estimate from data
- Not useful for practical predictions in field rides



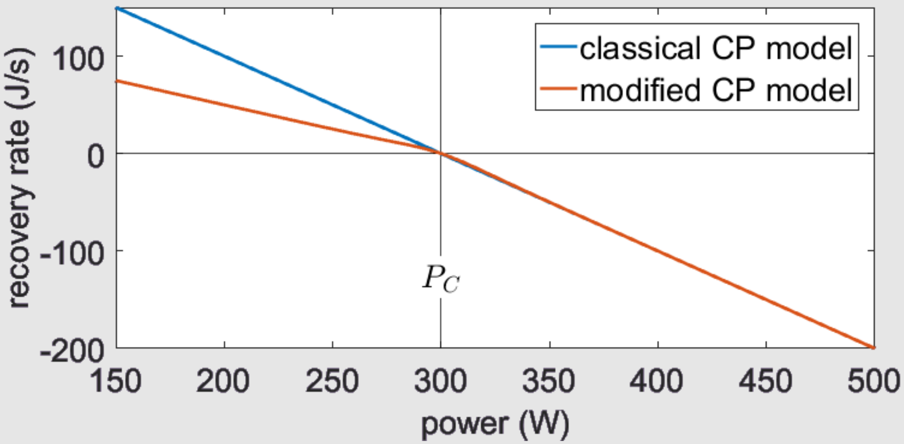
[1] Morton, R. Hugh (2006). "The critical power and related whole-body bioenergetic models". European Journal of Applied Physiology 96.4, pp. 339–-354.

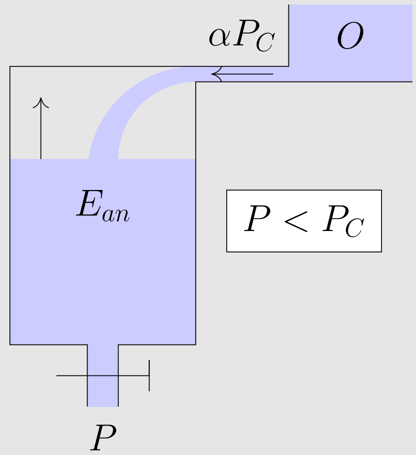
Practical compromise

Modified critical power model

- Initial anaerobic work capacity: $e_{an}(0) = E_{an}$
- Recovery rate for subcritical power $P < P_c$, damping factor $0 < \alpha < 1$
- Model parameters: P_c, E_{an}, α

$$\dot{e}_{an}(t) = \begin{cases} -(P(t) - P_c) & P(t) \geq P_c \\ -\alpha(P(t) - P_c) & P(t) < P_c \end{cases}$$



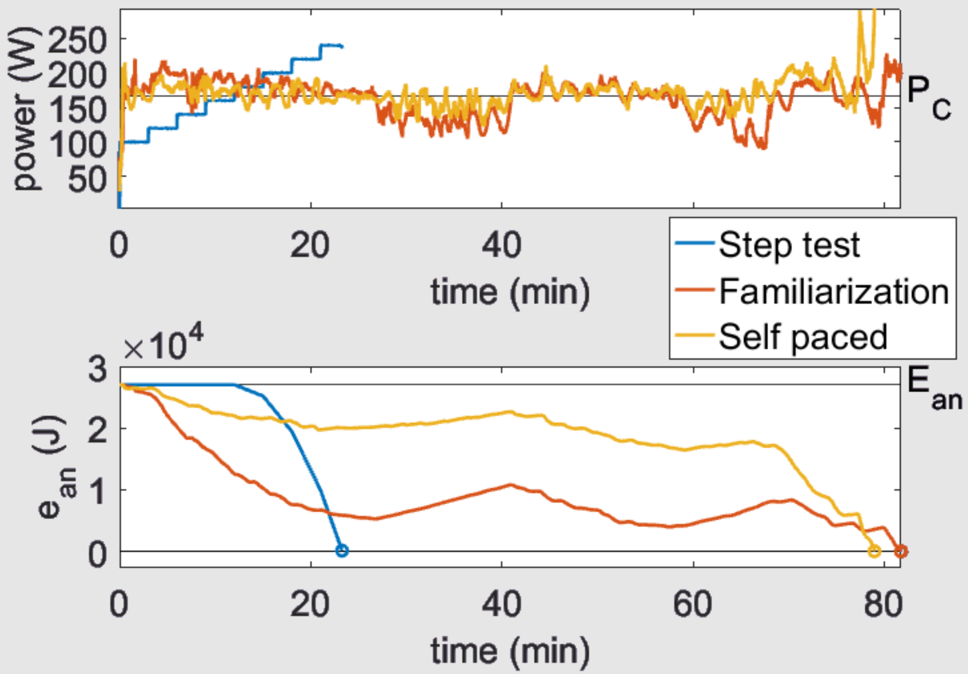


[1]Wolf, S., Bertschinger, R., Saupe., D. "Road cycling climbs made speedier by personalized pacing strategies." Proceedings of the 4th International Congress on Sport Sciences Research and Technology Support (2016): 109-114

Estimating parameters (P_c, E_{an}, α)

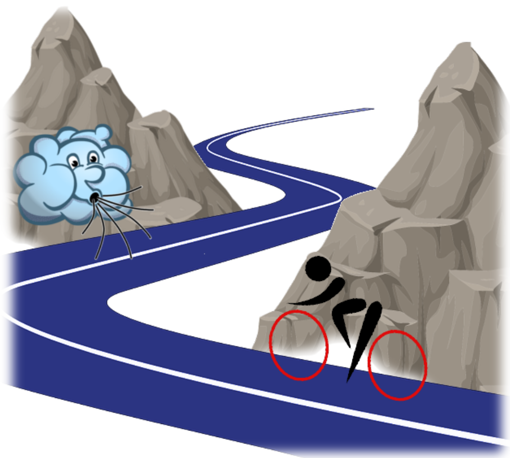
Tests with all-out efforts

- Ergometer ramp tests + simulator rides + field rides
- Numerically, find (P_c, E_{an}, α) with $e_{an}(t_f) = 0$ at finish time t_f.

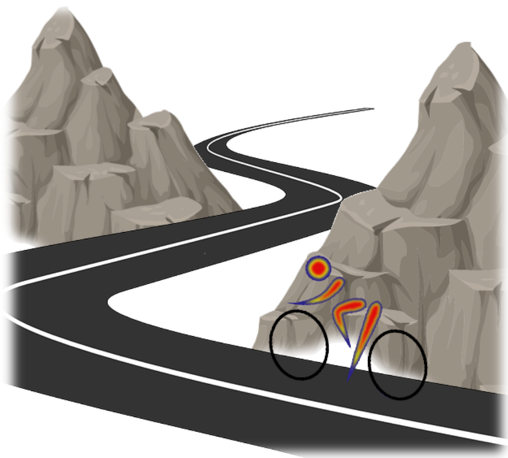


Optimal pacing strategies

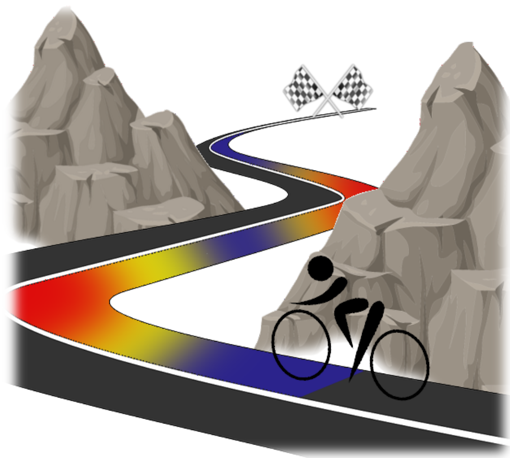
Physical model



Physiological model



Optimal control



Optimal pacing strategy

- Minimal time t_f to complete course
- Observe bounds $0 \leq e_{an}(t) \leq E_{an}$

$\Rightarrow$ Optimal control problem

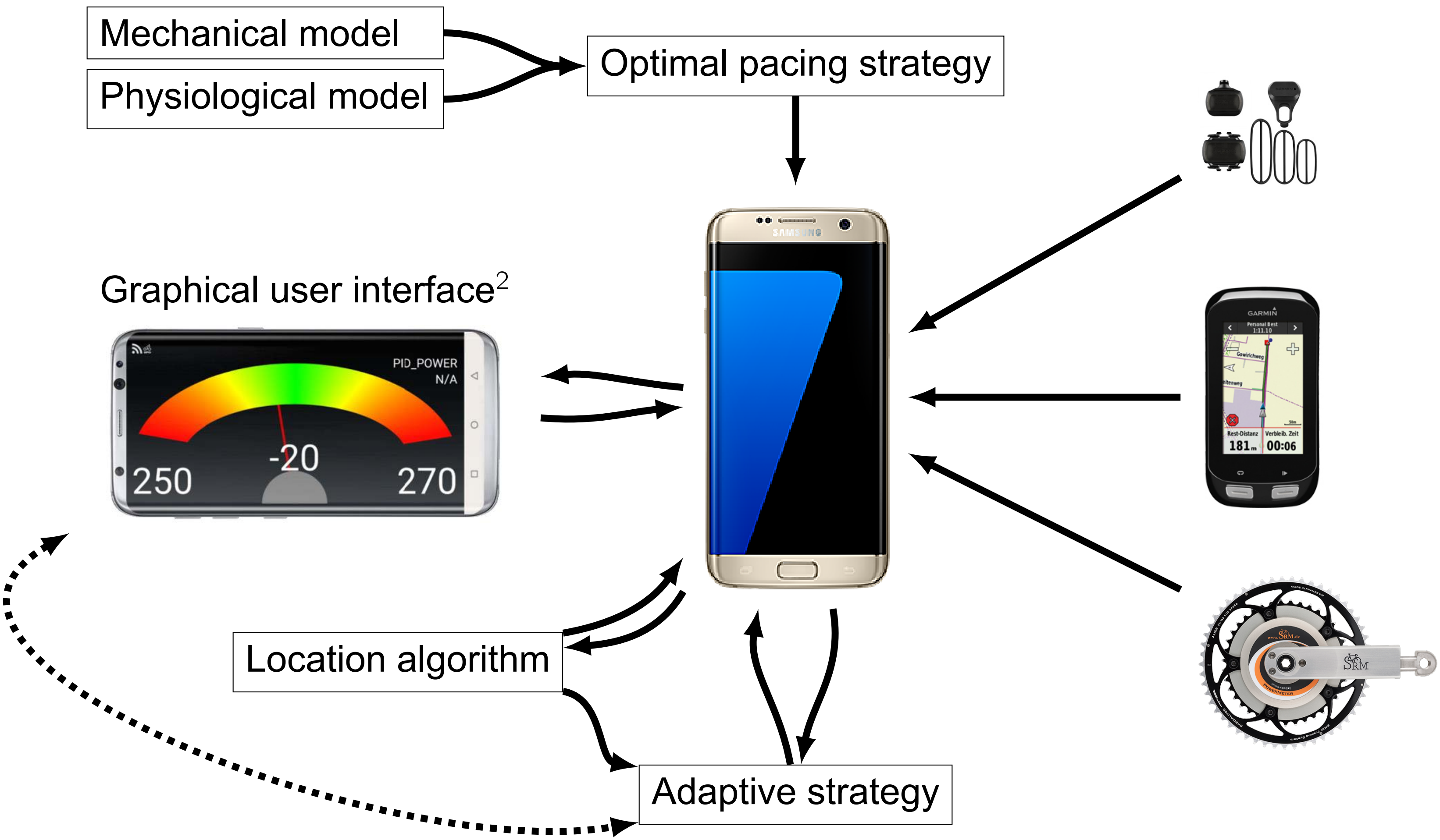
- Numerical solver: GPOPS-II[1]

Real-time adaptation of optimal strategy

- Proportional-integral-derivative controller (PID)
- Model predictive control (MPC)

[1] RP Optimization Research LLC, www.gpops2.com

Adaptive strategies and Android-based[1] feedback



[1]Dobiasch and Baca. “Pegasos –- Ein Generator für Feedbacksysteme”. Proc. Sportinformatik 2016.
[2]Artiga Gonzalez, Wolf, Bertschinger, Saupe. “Visual Feedback for Pacing Strategies in Road Cycling”. Proc. spinfortec (2018), to appear.

Putting it into practice: A pilot study

Questions asked

- Is it feasible to follow an adaptive pacing strategies in the field?
- What is the prediction quality?
- What are the critical issues of the technology?

Field study

- Selected 8 Strava segments for calibration and testing (Spring 2018)
- Additional ergometer rides for calibration.
-

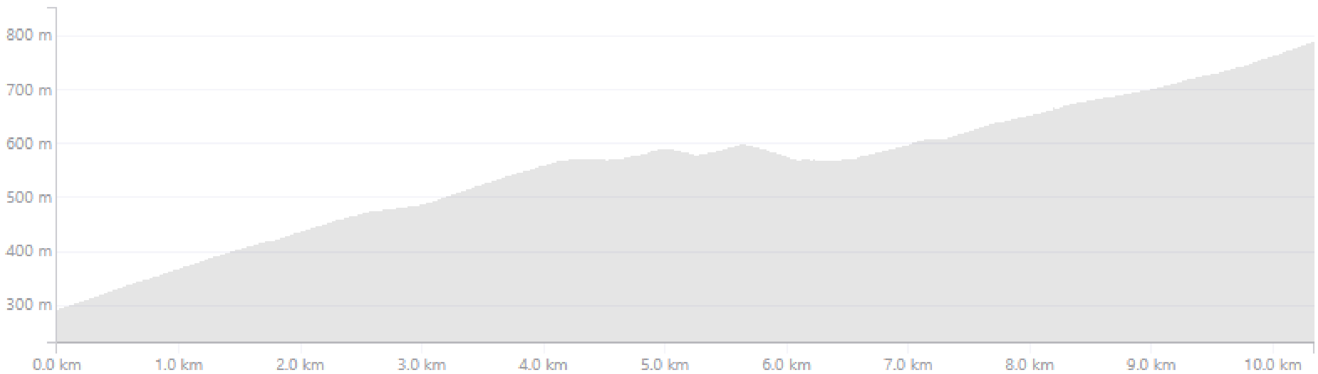
		name	distance	avg grade
		Temisas Climb-1	10.34 km	5%
		GC-65 Rociana (Bridge) to San Bart (Junction)	4.50 km	5%
		Ayagaures Climb	3.81 km	6%
		GC-60 San Bartolome Bridge to Viewpoint	5.02 km	7%
		Subida Cruz de Tejeda	4.62 km	6%
		551/65 cross to 65/60 cross	17.92 km	3%
		Oberegg-St Anton	2.57 km	8%
		the beautiful story for ugly kids	4.54 km	7%

used for optimal feedback
used for parameter estimation

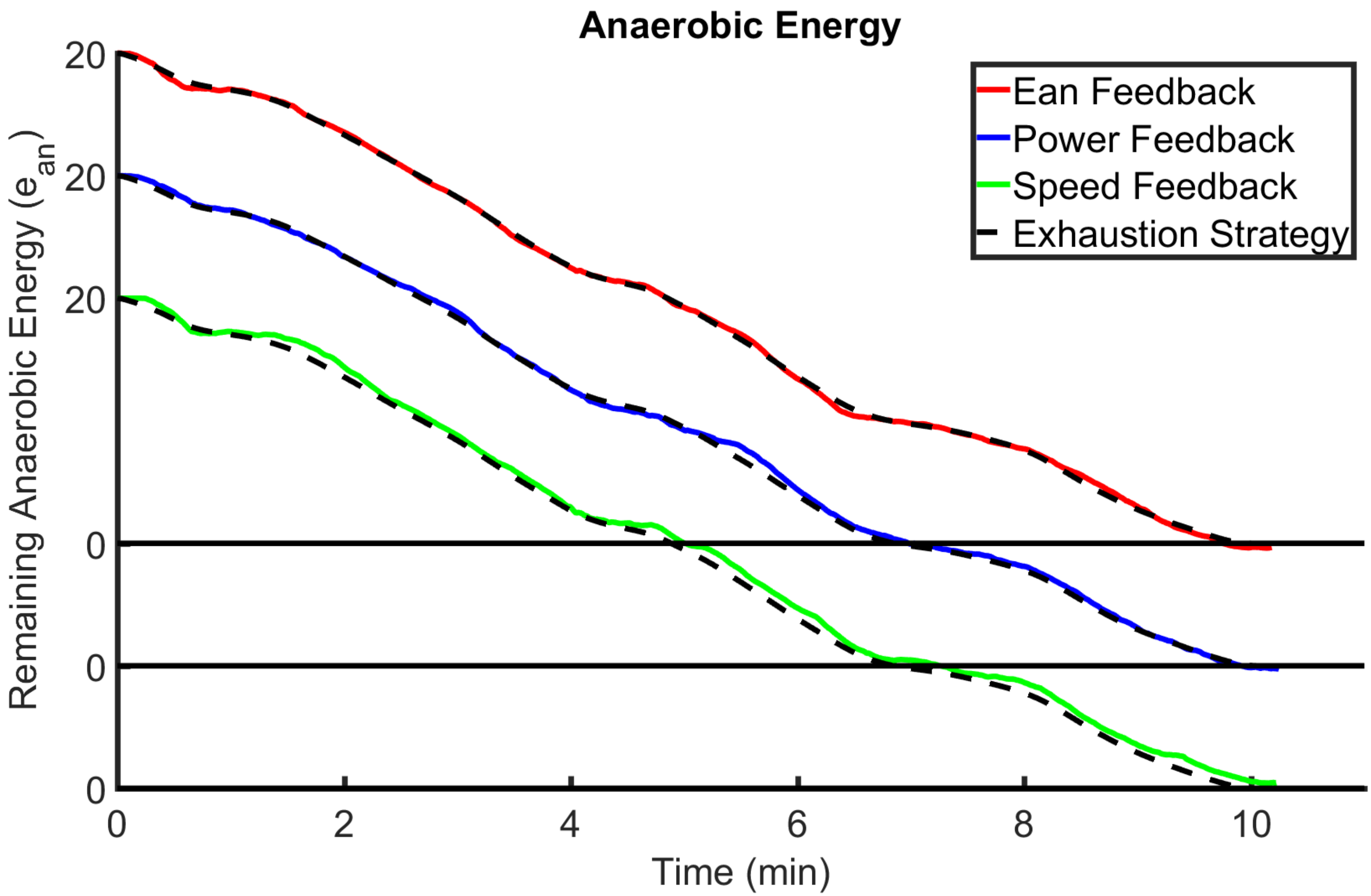
Temisas Climb-1

Ride Segment Agüimes, Canarias, Spain

10.34km	5%	292m	788m	496m	2	
Distance	Avg Grade	Lowest Elev	Highest Elev	Elev Difference	Climb Category	6,347 Attempts By 3,866 People



How well can one follow a strategy?



Feedback Results Overview

Ride vs. model

Testing the physical modeling (predicting speed and time from power)

	speed		power		time	
segment	rmse (m/s)	me (m/s)	rmse (W)	me (W)	abs (s)	rel (%)
GC-65 Rociana ...	0.56	-0.15			24	2.75
Ayagaures Climb	1.05	-0.53			66	8.57
GC-65 Rociana ...	0.58	-0.15			20	2.36
GC-60 San Bar ...	0.43	-0.05			18	1.55
Temisas Climb-1	0.70	-0.18			47	2.30

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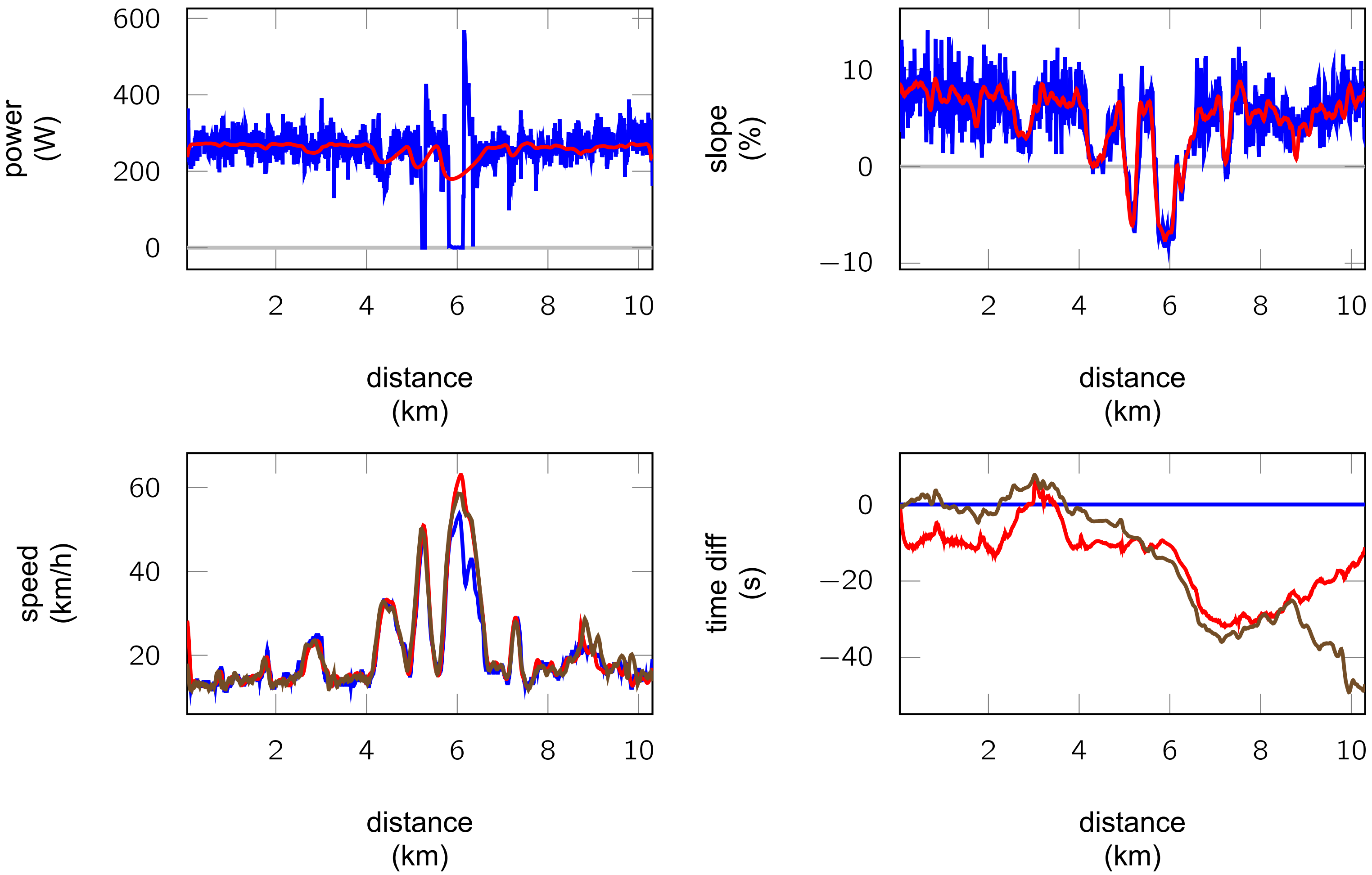
Ride vs. optimal strategy

Testing the feasibility (precision of following the strategy)

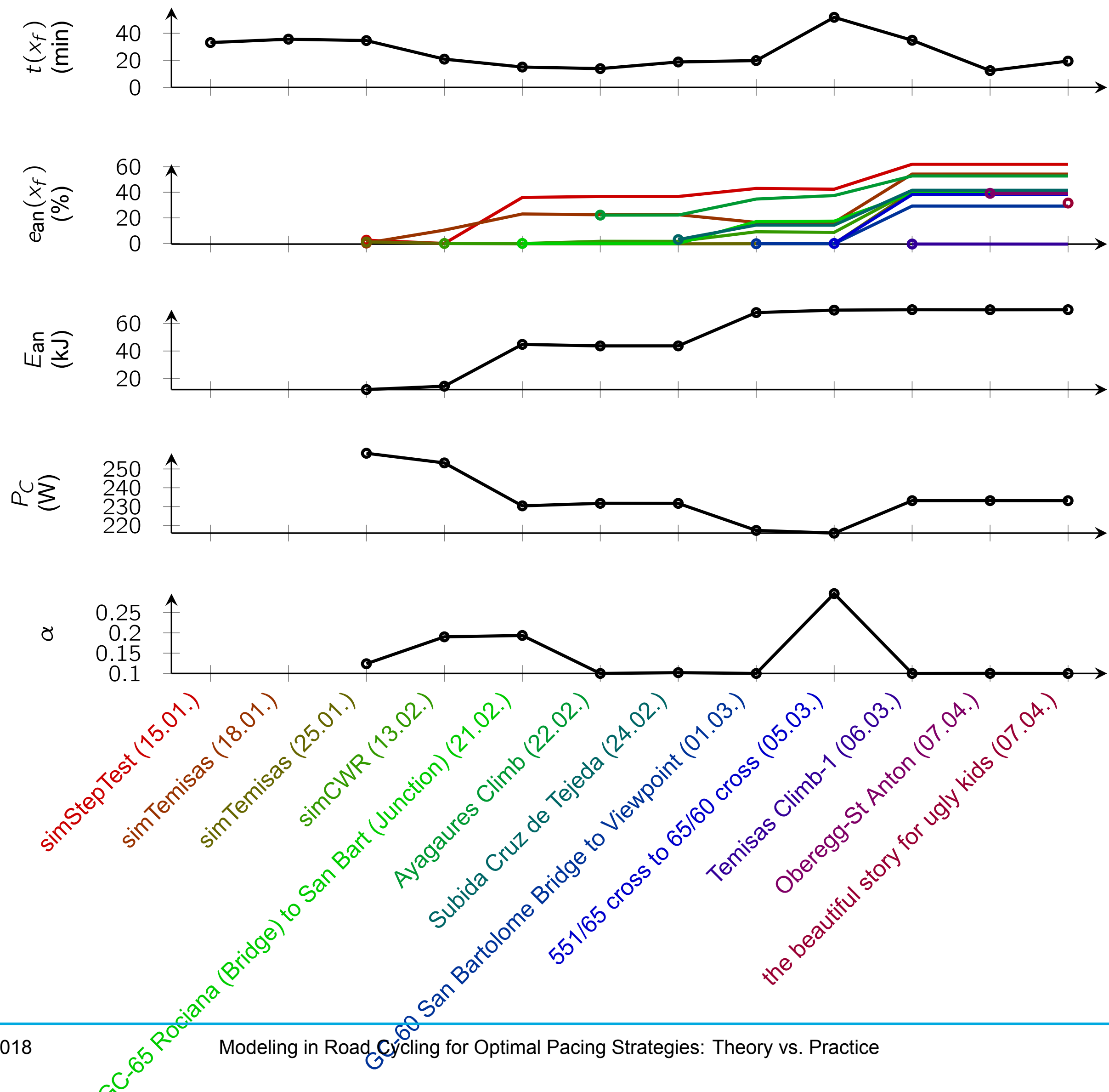
	speed		power		time		Feedback
	rmse	me	rmse	me	abs	rel	
segment	(m/s)	(m/s)	(W)	(W)	(s)	(%)	
GC-65 Rociana ...	0.61	-0.19	45	2	31.21	3.58	Ean
Ayagaures Climb	1.44	-0.88	68	-16	101.71	13.93	Ean after 2/3 speed
GC-65 Rociana ...	0.52	0.07	55	19	-14.93	-1.71	Power w/o control
GC-60 San Bar ...	0.51	-0.20	32	-7	53.76	4.73	Ean
Temisas Climb-1	0.66	-0.13	44	3	11.21	0.54	Power w/ control

Feedback results on segment Temisas Climb-1



blue: measurement red: optimal strategy brown: model based on power measurements

Physiological model parameters



Conclusions

Findings

- Models/feedback work quite well with riders in general
- Applicable to uncontrolled conditions with limitation
- Feedback using W-prime works well
- Downhill parts are difficult to model (braking)
- Time differences between prediction and ride
- Calibration of physiological model (difficult) requires rides of similar length

> With proper model parameter selection and visual feedback with respect to an optimal pacing strategy, significant performance gains for uphill time-trials of hobbyist, amateur, and perhaps also professional athletes can be expected.

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Current / future work

- Visual feedback interface has been improved
- Large field study (16 participants) ongoing
- Development/testing of a (simplified) App for Garmin devices active
- Dissemination to hobby/amateur riders planned

Thank you!