State of the art in aerodynamic measurement

challenges and opportunities

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Goals of presentation

- Understand how basic technologies work
- Understand and overcoming limitations
- Road testing as part of aero strategy
- Help in our selection of technology
- Opportunities

How can we test

- Wind tunnel
- Indoor Velodrome
- Outdoor Velodrome
- Road testing
- Race

- Which is best ? None
- Make sure your race results match your tests
- Test where you plan to race !!!

A few abbreviations

- Mass m
- Gravity 9.81m/s^2 g
- Ground Speed V_g
- Air Speed = Ground Speed+Wind. V_a
- Air Density rho

4 Buckets of power

$P_{total} = P_{rr} + P_{incline} + P_{air} + P_{acc}$

P_{total}	measured by powermeter
P_{rr}	$m * g * CRR * V_g$
$P_{incline}$	$m * g *$ deltaAlt
P_{air}	$0.5 * rho * CDA * V_a\text{^}2 * V_g$
P_{acc}	$0.5 * m * (Vf\text{^}2 – Vi\text{^}2)$

Calculating CDA

$$P_{air} = P_{total} - P_{rr} - P_{incline} - P_{acc}$$

$$CDA = \frac{P_{total} - P_{rr} - P_{incline} - P_{acc}}{0.5 * rho * V_a\text{^}2 * V_g}$$

360w, 50km/h, no incline, steady

$P_{total} = P_{rr} + P_{incline} + P_{air} + P_{acceleration}$

rr	75 * 9.81 * 0.0035 * 14	= 36w
incline		= 0w
air	0.5 * 1.18 * .200 * 2744	= 324w
acc		= 0w
	Total	360w

Introduce a 1% incline

$P_{total} = P_{rrr} + P_{incline} + P_{air} + P_{acc}$

rr	75 * 9.81 * 0.0035 * 14	= 36w
inc	75 * 9.81 * .14	= 103w
air	0.5 * 1.18 * .200 * 2744	= 324w
acc		= 0w
	Total	463w

Back to 360w

$P_{total} = P_{rr} + P_{incline} + P_{air} + P_{acc}$

rr	75 * 9.81 * 0.0035 * 14	=	36w
inc	75 * 9.81 * .14	=	103w
air	0.5 * 1.18 * .200 * 2744	=	324w
acc	0.5 * 75 * (13.9^2 – 14^2)	=	-103w
		Total	360w

Calculating CDA

$$P_{total} = P_{rr} + P_{incline} + P_{air} + P_{acc}$$

rr	75 * 9.81 * 0.0035 * 14	=	36w
inc	75 * 9.81 * .14	=	103w
air	0.5 * 1.18 * .200 * 2744	=	324w
acc		=	0w
			463w

CDA = (463-36 -103 -0) / (0.5 *1.18*2744)

= 0.200

How do we measure

- Power
  - **Need to remove losses due to drive train inefficiency**
- Speed
  - **Speed sensor**
  - **GPS**
- AirSpeed
  - **Pitot, Weather Flow**

- Air Density
  - **Temp, humid, baro pressure**
- Incline
  - **Baro**
  - **IMU gyro, accelerometer,mag**

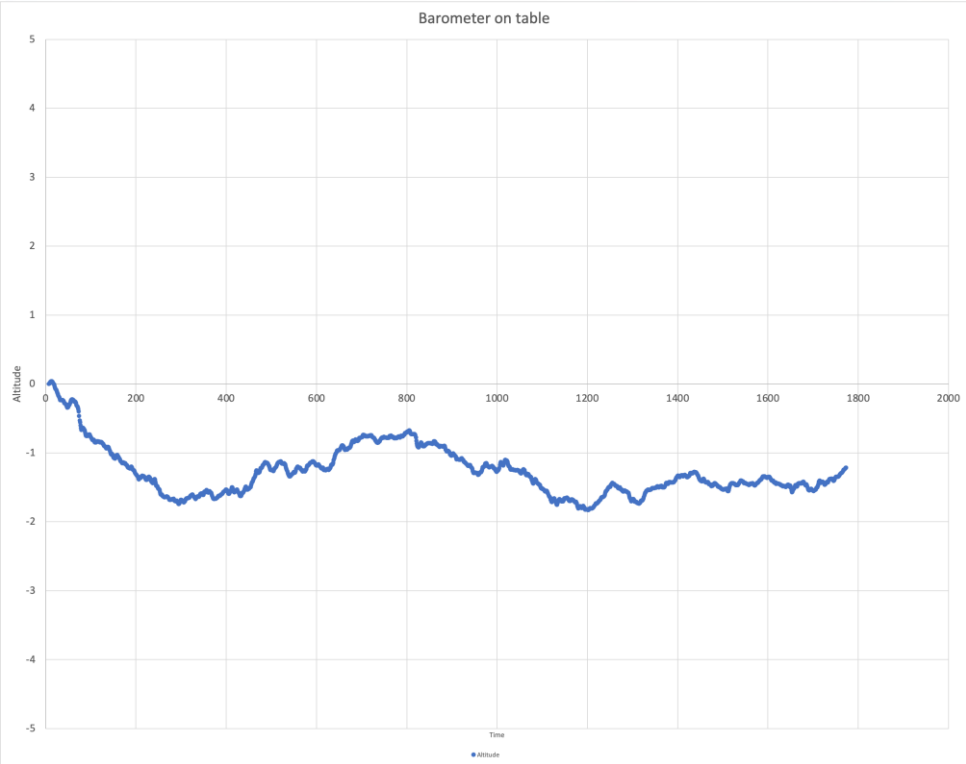
Sources of error

- Power
  - **Calibration/autoCalibration**
- Speed
  - **Speed sensor resolution +/- 1 count**
  - **GPS 10m**
- AirSpeed
  - **Yaw**
  - **Rider Position**
- Air Density
  - **Temp, humid, baro pressure**
- Incline
  - **Baro**
  - **IMU gyro, accelerometer,mag**

Other Challenges

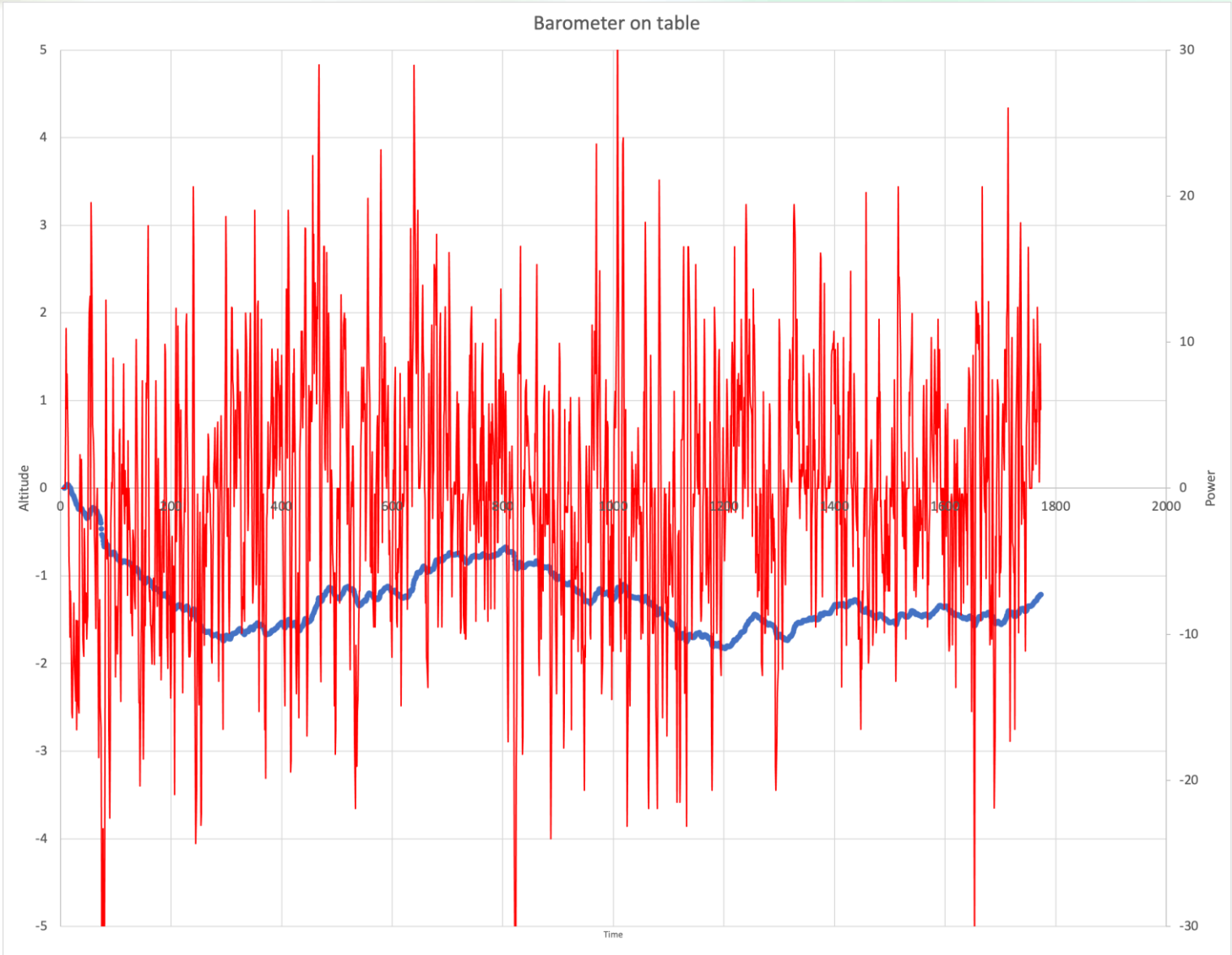
- Complexity of overall system
- Placement of sensor on bike,
  - **Clean air**
  - **Minimal vibration**
  - **Complex front ends**
  - ….
- Position changes of the rider

Explore error : Barometer



- 2m drift over 30min

Converting to watts



Introduce error from barometer

$P_{total} = P_{rr} + P_{incline} + P_{air} + P_{acceleration}$

CRR	75 * 9.81 * 0.0035 * 14	=	36w
ALT	75 * 9.81 * (.14+.05)	=	140w
AIR	0.5 * 1.18 * .200 * 2744	=	324w
ACC		=	0w

CDA = (463–36 –140-0) / (0.5 * 1.18 * 2744)

CDA = 0.177

Explore error : wind speed

$P_{total} = P_{rr} + P_{incline} + P_{air} + P_{acceleration}$

CRR	75 * 9.81 * 0.0035 * 14	=	36w
ALT	75 * 9.81 * (.14)	=	103w
AIR	0.5 * 1.18 * .200 * 2744	=	324w
ACC		=	0w

1%	CDA = (463–36-103-0) / (0.5 * 1.18 * 2799) =	0.196
2%	CDA = (463–36–103-0) / (0.5 * 1.18 * 2854) =	0.192
10%	CDA = (463–36–103-0) / (0.5 * 1.18 * 3320) =	0.165

Real time-Instantaneous-Window

- Energy = power * time, 1w * 1s = 1 joule

$$P_{total} = P_{rr} + P_{incline} + P_{air} + P_{acc}$$

$$E_{total} = E_{rr} + E_{incline} + E_{air} + E_{acc}$$

4 buckets of energy

$$E_{total} = E_{rr} + E_{incline} + E_{air} + E_{acc}$$

E_{total} $\sum$ samples measured by powermeter

E_{rr} $\sum$ $m * g * CRR * V_g$

E_{inc} $\sum$ $m * g * dAlt$

E_{air} $\sum$ $0.5 * rho * CDA * V_a\text{^}2 * V_g$

$E_{ac} =$ $\sum$ $0.5 * m * (Vf\text{^}2 – Vi\text{^}2)$

airspeed = groundspeed + wind

4 buckets of energy

$$E_{total} = E_{rr} + E_{incline} + E_{air} + E_{acc}$$

E_{total} $\sum$ samples measured by powermeter

E_{rr} $\sum$ $m * g * CRR * V_g$

E_{inc} $\sum$ $m * g * dAlt$

E_{air} $\sum$ $0.5 * rho * CDA * V_a\text{^}2 * V_g$

$E_{ac} =$ $\sum$ $0.5 * m * (V_f\text{^}2 - V_i\text{^}2)$

airspeed = groundspeed + wind

4 buckets of energy

If dAlt = 0 and Vf = Vi

$E_{total} = E_{rr} + E_{air}$

E_{total} Σ samples measured by powermeter

E_{rr} Σ m * g * CRR * Vg

E_{air} Σ 0.5 * rho * CDA * Va^2 * Vg

airspeed =

groundspeed + wind

Role of protocol

How do we get there

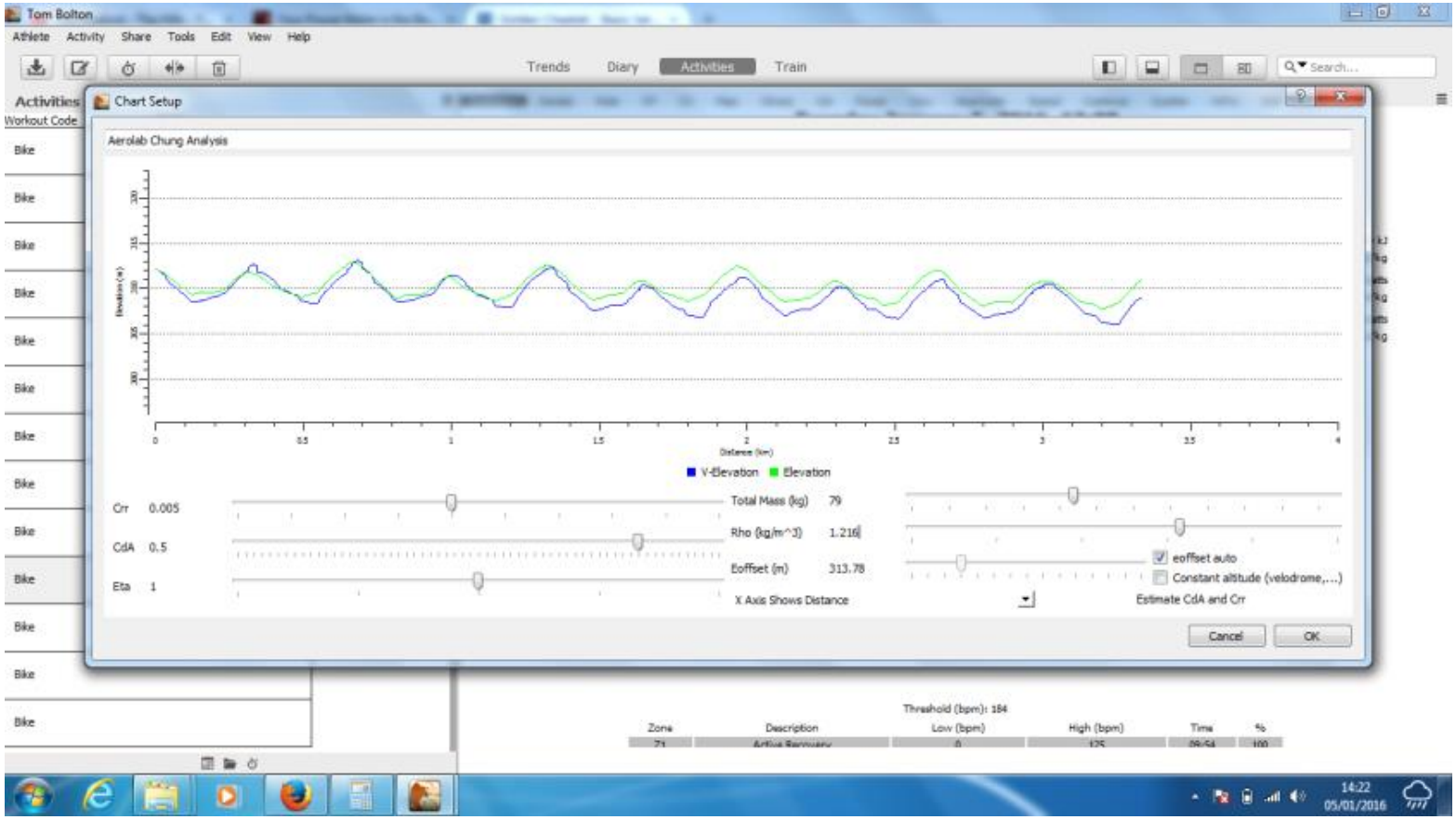
- Indoor Velodrome
  - Ground Speed = AirSpeed
  - No delta Alt
- Close Loop
- Out and Back
  - Wind out ~= -1 * Wind back

Why is protocol not enough ?

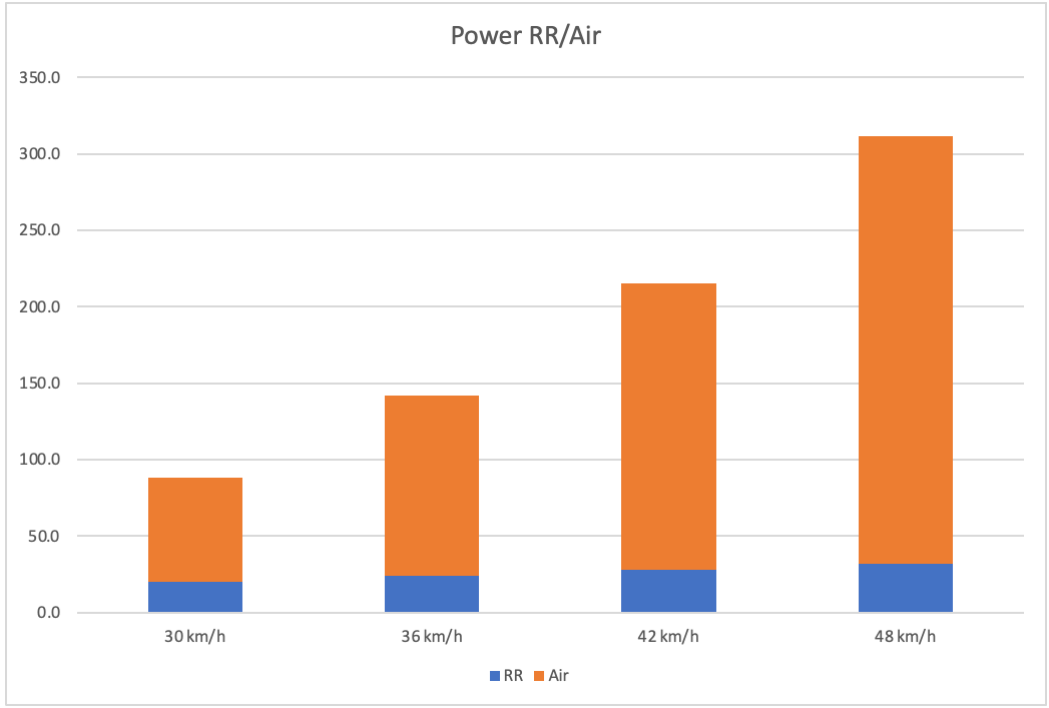
- What changes
  - **Yaw**
  - **Position**
  - **Rolling resistance**

- Error analysis

What is the Chung method

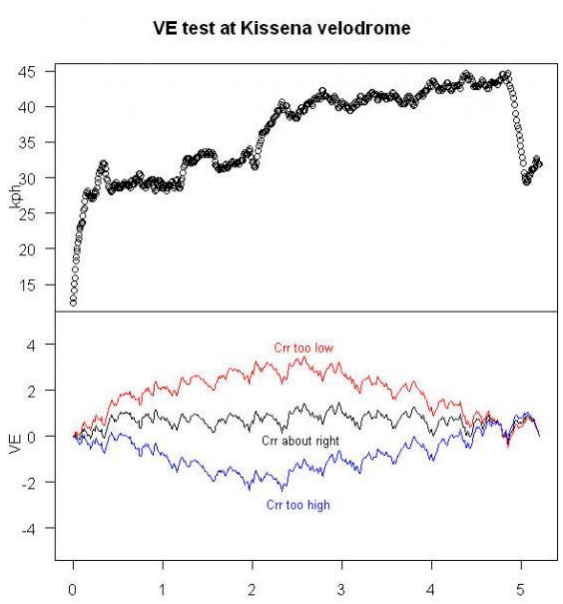


Fun fact – CRR / CDA relationship



- On topic of CRR : varies with temperature and vibration

Shen method


VE test at Kissena velodrome
kph
45
40
35
30
25
20
15
VE
4
2
0
-2
-4
Crr too low
Crr about right
Crr too high
0
1
2
3
4
5

Quantifying precision

Opportunities beyond CDA

- Measuring sources of inefficiency : position and biomechanics
- CRR, vibration, tire pressure
- Race results vs test – embedded tech
- TTT : optimize pacing and execution

To do : vendors

- more sensors, the more we can detect good and bad data
- Correct or at least quantify error
- Sophisticated fusion protocols
- Adjust to protocols
- Easy to use software
- More cost effective
- Cooperation/interoperability/open source

To do : users

- Select your technology
  - **Ease of use**
  - **Precision**
  - **Non intrusiveness**
  - ***Supports Protocol* you can live with**
  - **Actionable Information**
- Understand the limitations of the technology

Conclusions

- Make road testing part of your strategy
- Understand the role of protocol
- Pick the technology that meets your requirements today and will grow
- Slowly push the boundaries to new possibilities

Questions

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Credits

- https://poweredtemplate.com/02093/0/index.html
- https://bikeblather.blogspot.com/2013/08/aero-field-testing-using-chung-method.html
- Tom Bolton https://cycle4curry.wordpress.com/tag/chung-method/
- https://nyvelocity.com/articles/coachingfitness/the-shen-method