Aerodynamics of cycling
單車空氣動力學

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December 7, 2022

Aerodynamics
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Technology
Centre

Outline

- Introduction
- What is aerodynamics?
- Methods and tools of cycling aerodynamics
- Roles of cycling aerodynamics
- Summary

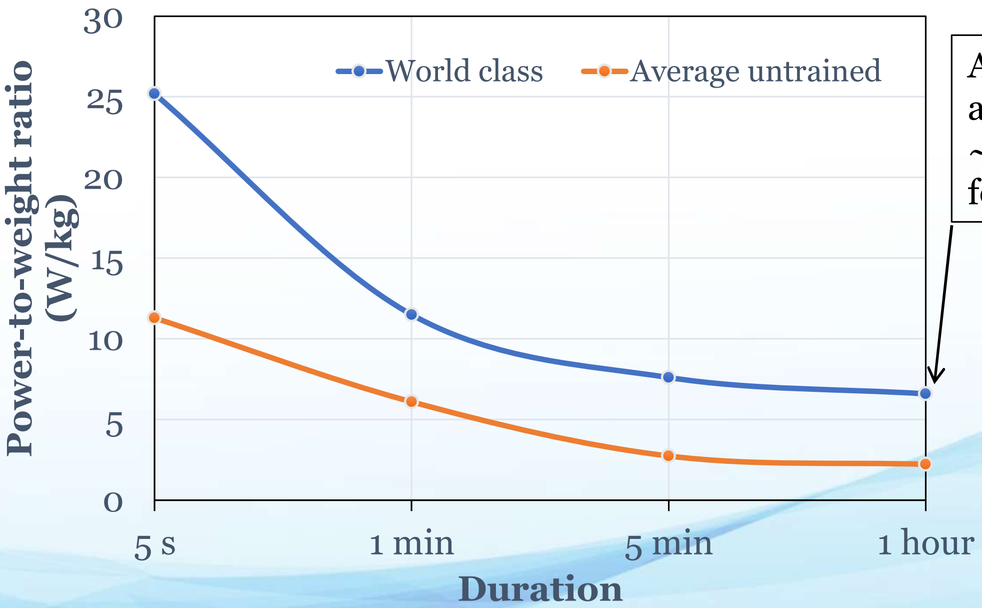
Introduction

Power in cycling

- In cycling, the mechanical power is generated by the cyclist.

Power = Propulsive force × Speed

- The maximum power output by a cyclist is dependent on the duration.



A 60 kg world-class athlete can sustain ~**400W** power output for an hour (**6.6W/kg**).

As a comparison, for a passenger car (BMW 320i):

- Maximum power = 137 kW
- Weight = 1530 kg
- Power-weight ratio = **90 W/kg**

https://www.trainingpeaks.com/blog/power-profiling/

Chronicle of cycling

Germany
First bicycle
"Hobby horse"
1817

France
Pedals
"Boneshaker"
1863

Britain
Big front wheel
"Penny farthing"
1880

Britain
Gear & chain
"Safety bicycle"
1885

Britain
John Boyd Dunlop
Pneumatic tyre
1888

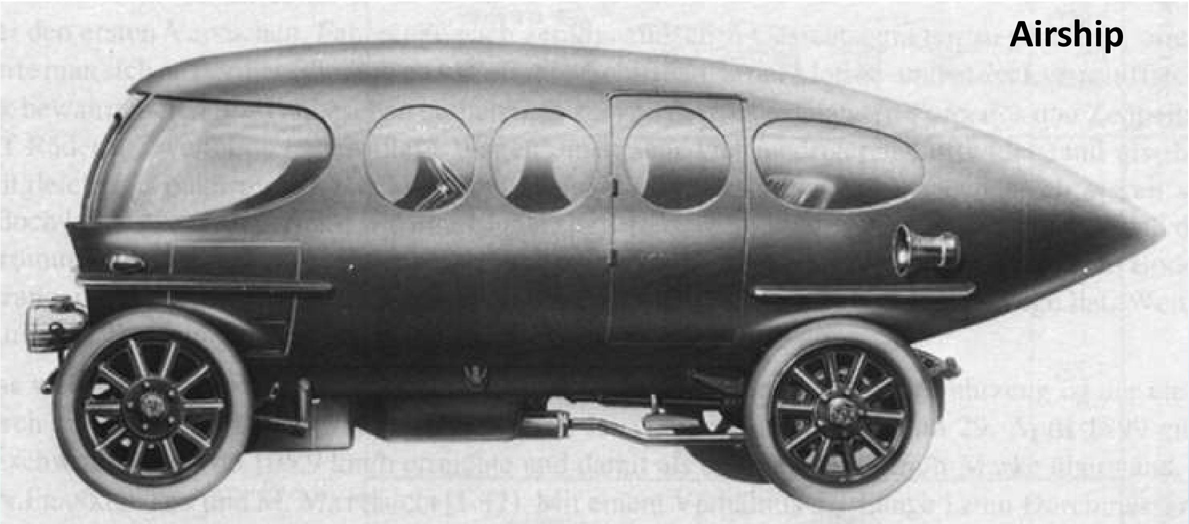
~1978
Skinsuit

~1984
Aero-helmet

2022-10-08

56.792 km/h = 15.776 m/s

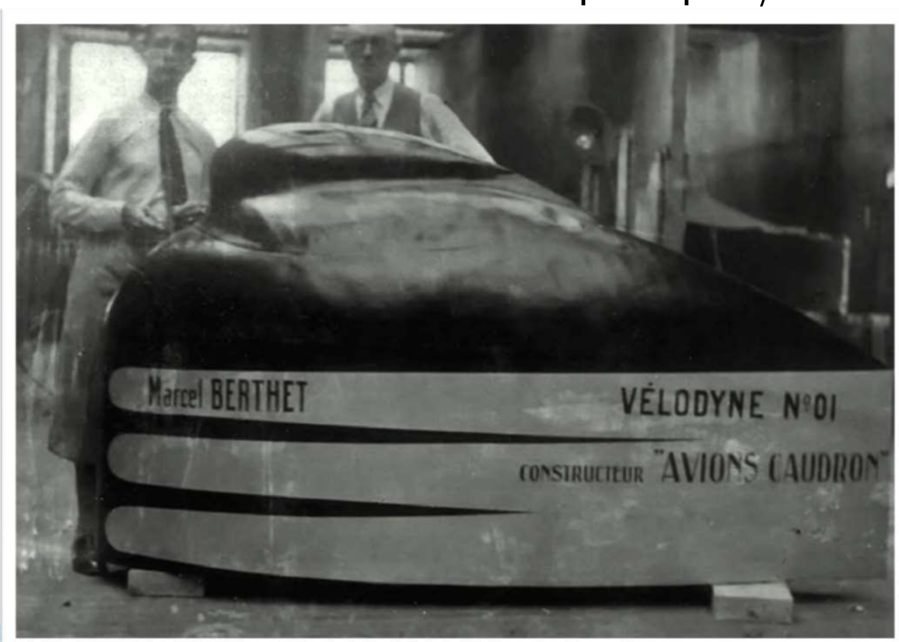
Early aero development mirrored passenger car development in earlier 1900s



Aero-related improvements in 1900s

1913, world record, 5km in 5’39”,
53.1 km/h

1933, hour record for “special bikes with device to reduce air resistance”: 48.604 km/h

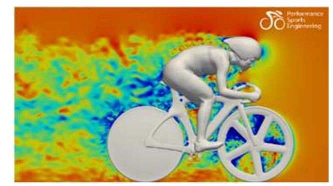


Due to their huge aerodynamic benefits, in 1914, the UCI **banned** aerodynamic devices in normal cycling races.

Hadland, T., & Lessing, H. E. (2014). *Bicycle design: An illustrated history*. MIT Press.

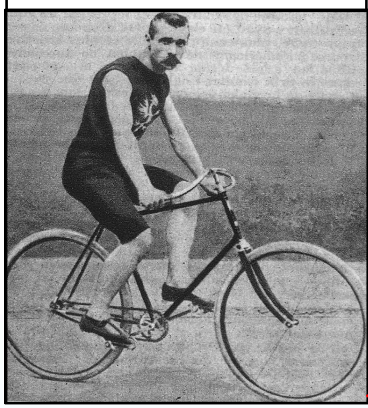
Power balance in cycling

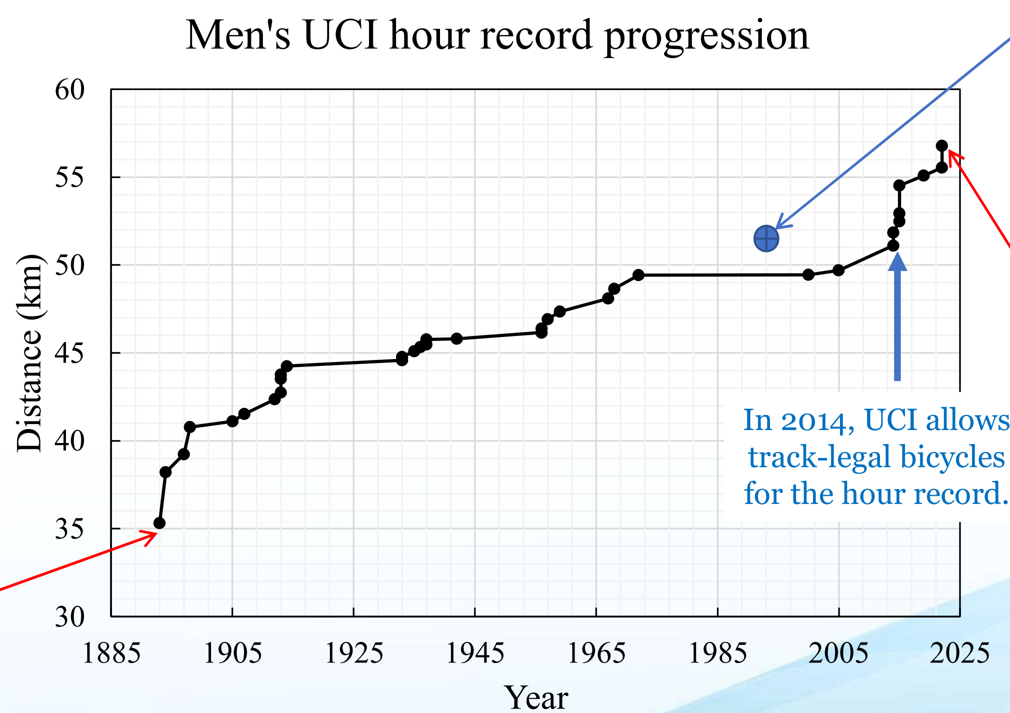
- Athlete power output
  - Power for acceleration
  - Power for losses
    - Aerodynamic resistance
    - Rolling resistance
    - Power transmission loss
  - Power for potential energy



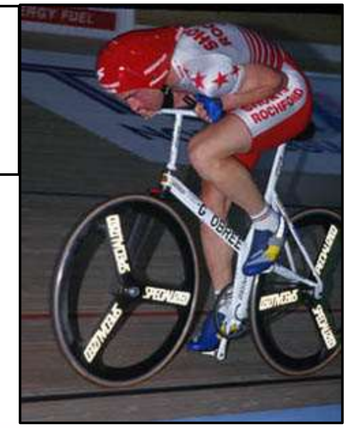
The importance of aerodynamics

1st hour record:
Henri Desgrange
(1893, 35.525 km)





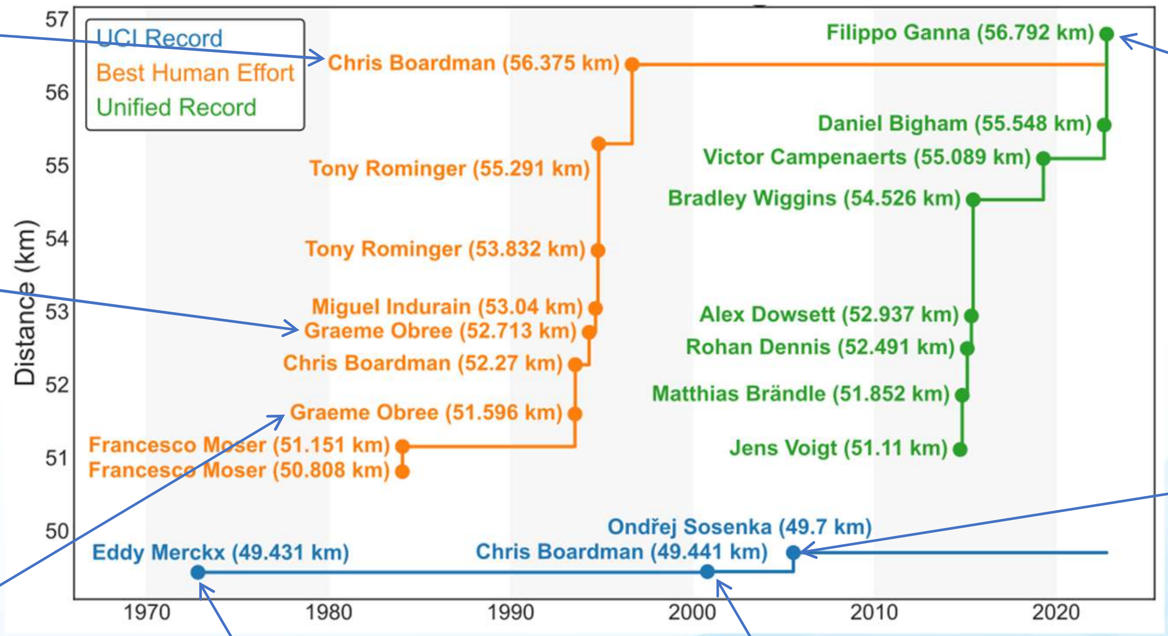
Graeme Obree
(1993, 51.596 km)
Record later **cancelled** by UCI



Latest official hour record:
Filippo Ganna
(2022, 56.792 km)

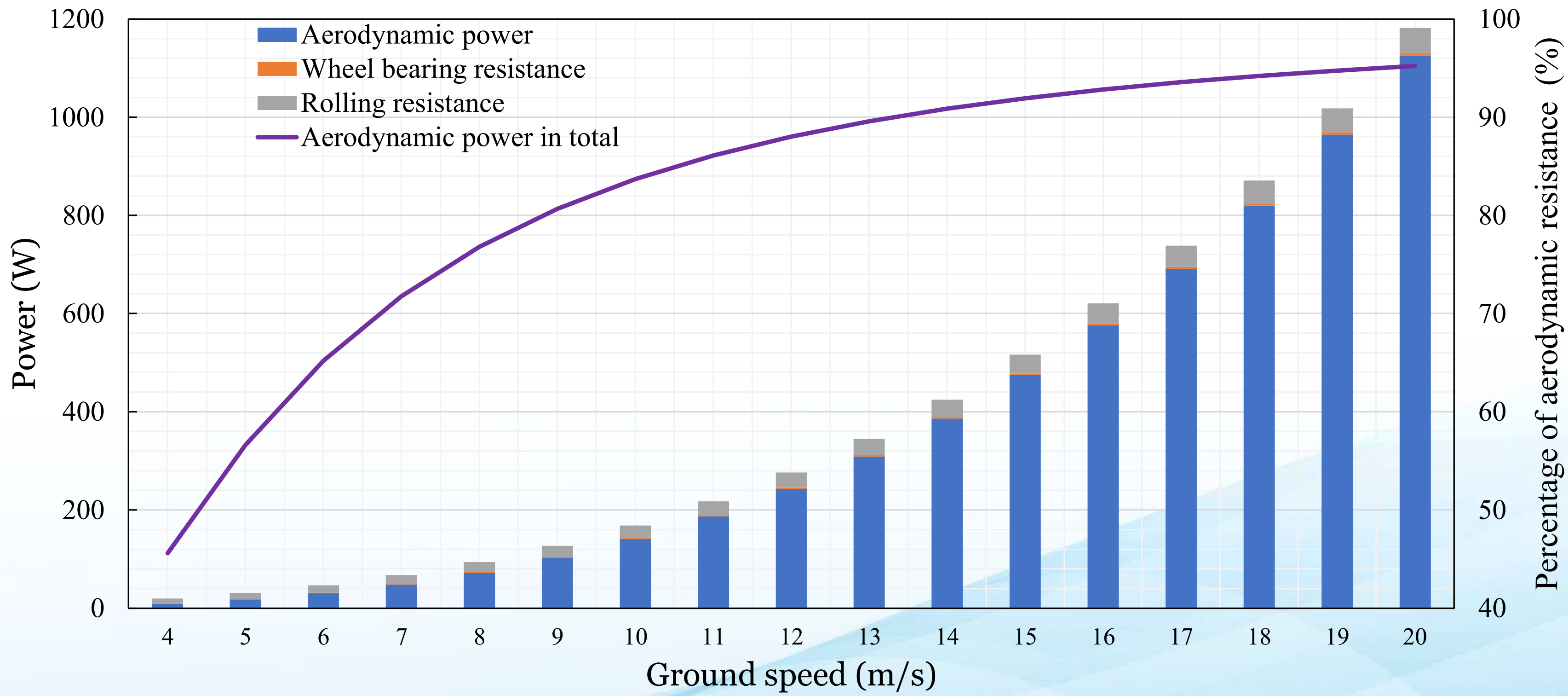
Reducing the aerodynamic drag will lead to huge benefits.

The importance of aerodynamics



Hour record. (2022, October 20). In *Wikipedia*. https://en.wikipedia.org/wiki/Hour_record

The importance of aerodynamics

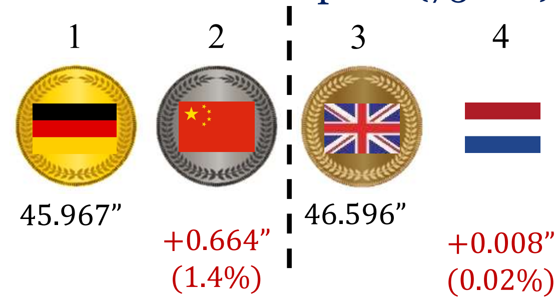


The aerodynamic drag is increasingly important at higher speeds.

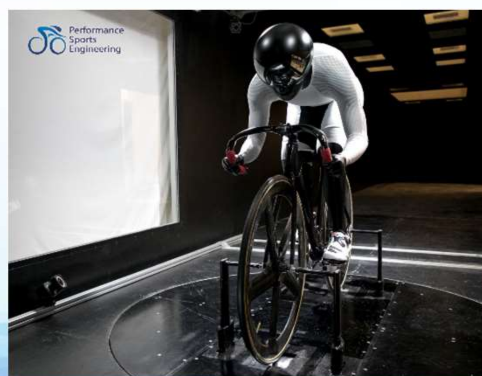
The importance of aerodynamics

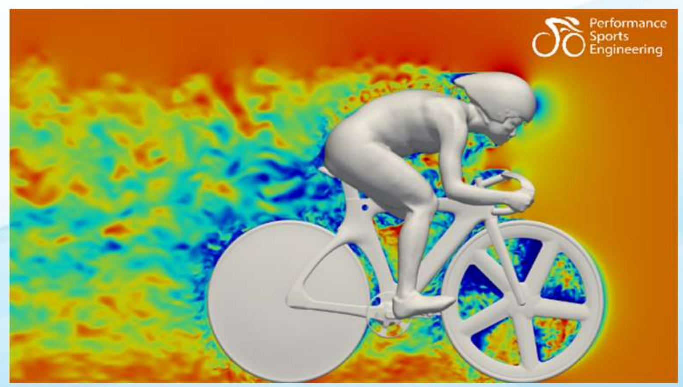
- Aerodynamics provide marginal gains
  - The gold and the bronze are within milliseconds.
  - Winning margin is usually within 2% of the racing time.

2022 UCI Track Cycling World Championships
– Women's team sprint (750 m)



- Importance of aerodynamics
  - Aerodynamic drag: over 90% of total power consumption at high speed;
  - Under constant power assumption, every 3% drag reduction ⇒ 1% time saving.





Basic aerodynamics

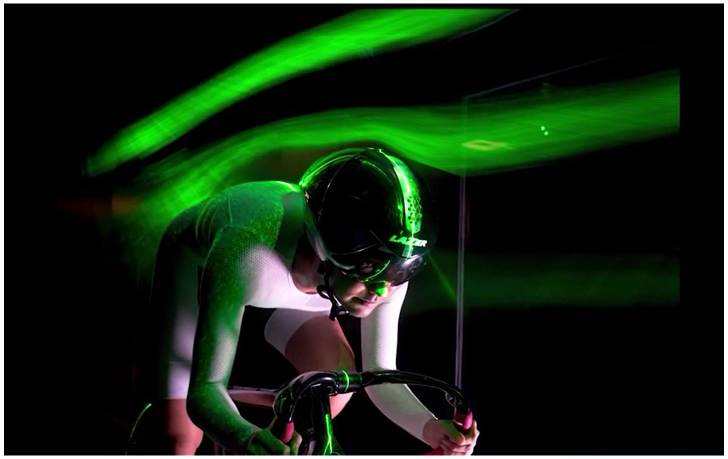
- What is aerodynamics?
- Important physical properties

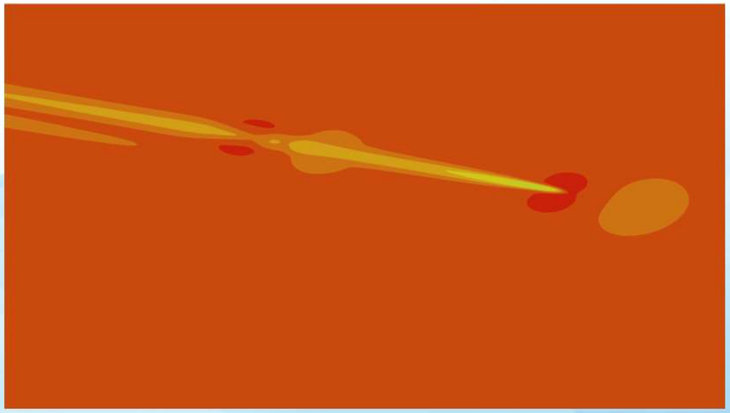
What is aerodynamics?

- Concerns motion of fluids and their resultant forces + moments
- Subject to the fundamental laws of physics:
  - Newton’s laws of motion;
  - Laws of thermodynamic;
  - Conservation of mass/momentum/energy.
- Formula for the aerodynamic drag:

$$D = \frac{1}{2}\rho v^2 C_D A$$

D: aerodynamic drag (N)
ρ: air density (kg/m^3)
v: cycling speed (m/s)
C_D: drag coefficient (1)
A: frontal area (m^2)

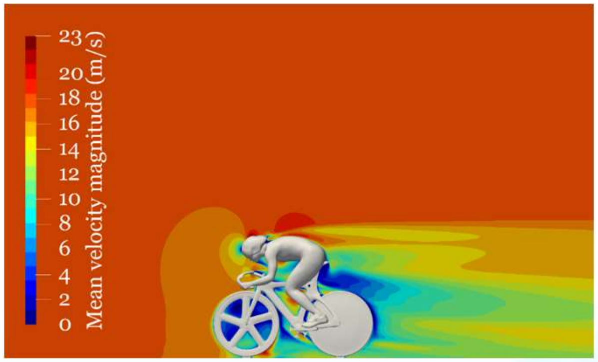




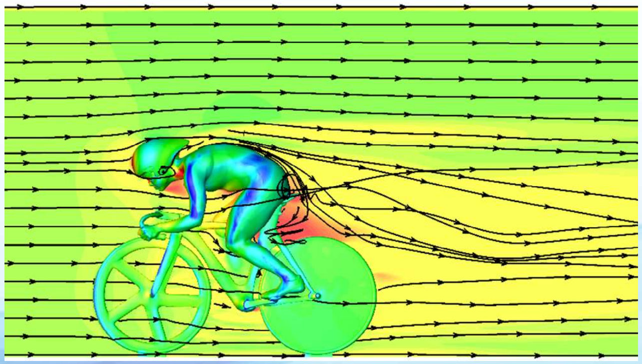
Mean velocity field around dual cyclists

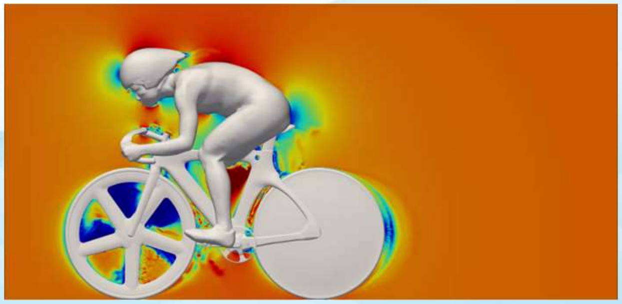
Velocity (m/s)

- Velocity is the rate of change of the position of an object.
- Velocity is a vector quantity whose:
  - magnitude is the speed;
  - direction is the direction of motion.
- Field representation:
  - Steady flows: $\vec{v} = \vec{v}(x, y, z)$
  - Unsteady flows: $\vec{v} = \vec{v}(x, y, z, t)$



Mean velocity field around a cyclist


Streamline illustration

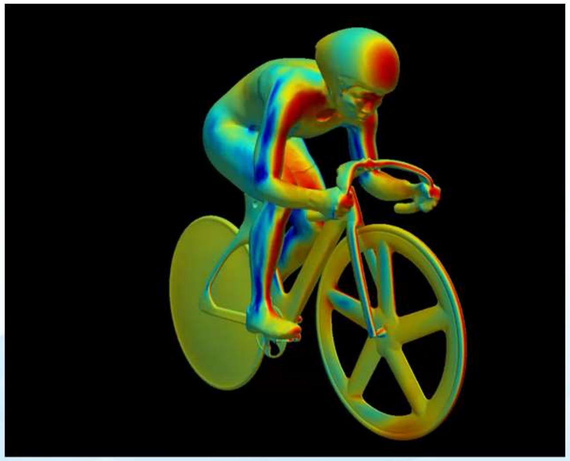

Unsteady velocity field

Pressure

- Pressure is the normal force exerted by a fluid per unit area.
- Unit: newtons per square meter (N/m^2)
  - Pascal (Pa): $1\ Pa = 1\ N/m^2$;
  - Standard atmosphere (atm): $1\ atm = 101{,}325\ Pa$;
- Terms:
  - Static pressure is the pressure exerted by a fluid when it is at rest;
  - Dynamic pressure describes the kinetic energy per unit volume of a fluid particle;

$$p_{dynamic} = \frac{1}{2}\rho v^2 \ (\rho\text{: density, } v\text{: flow speed})$$

  - Total pressure = static pressure + dynamic pressure.

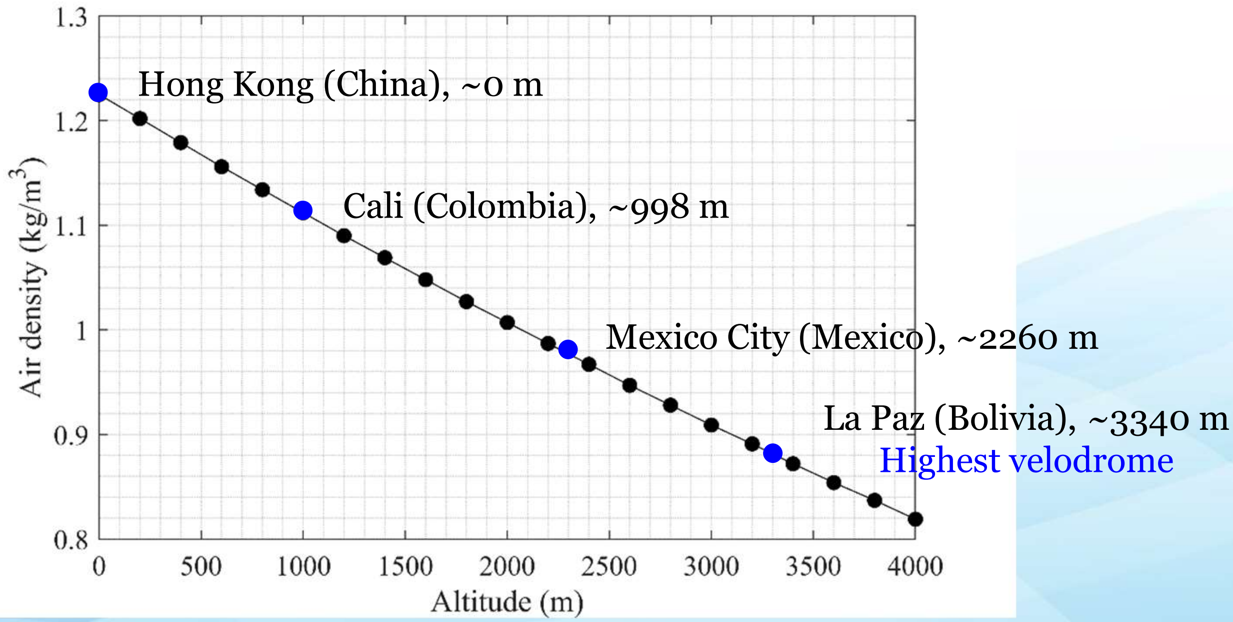


Red: high pressure region
Blue: low pressure region

Density

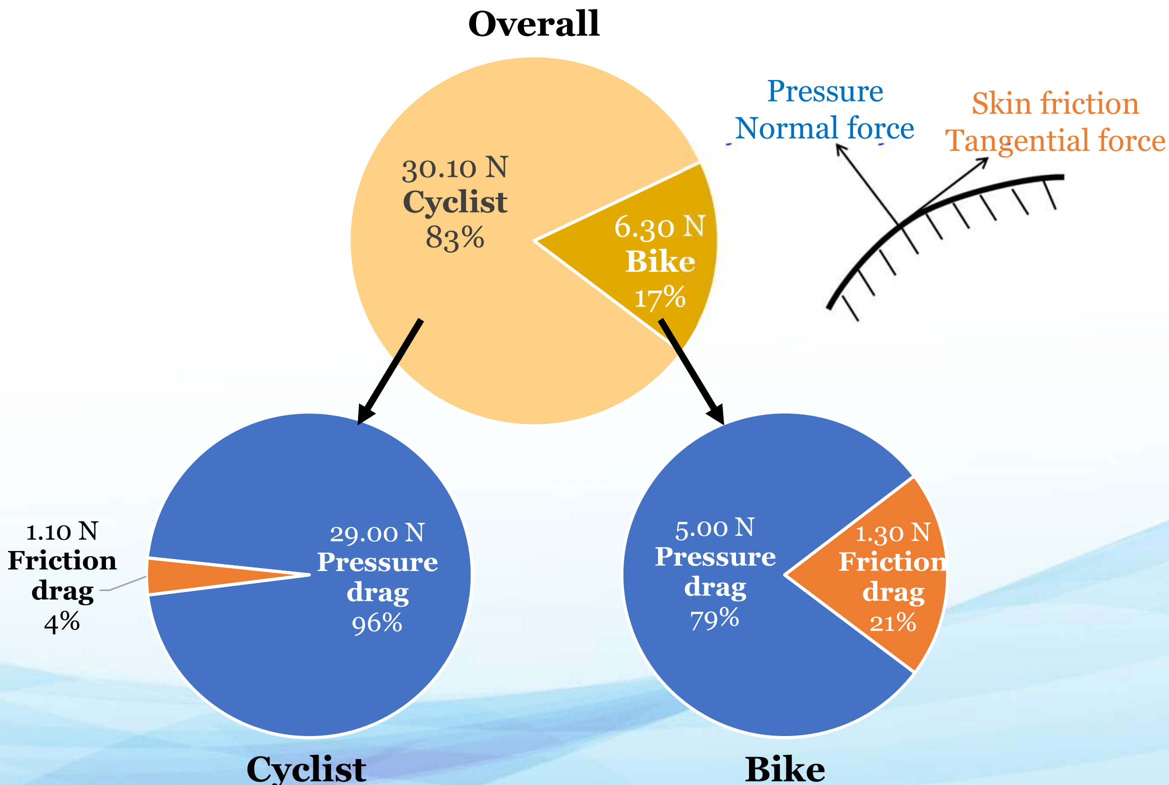
- Density is the mass per unit volume in kilograms per cubic meter (kg/m^3)
- Air density is affected by altitude, pressure and temperature.

Density vs. Altitude and famous velodromes around the world

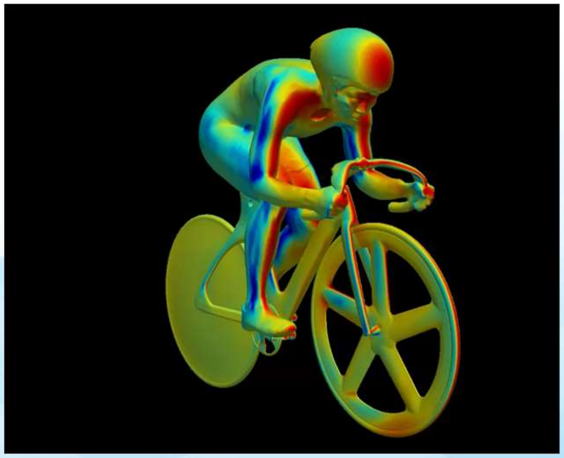


Composition of aerodynamic drag (N)

- Aerodynamic drag decomposition of a track cyclist at 17 m/s:



- Skinsuit design target:
  - Reduction on skin friction drag has a minor effect;
  - Different fabric pattern will affect the flow separation location and therefore, the pressure distribution on the cyclist.

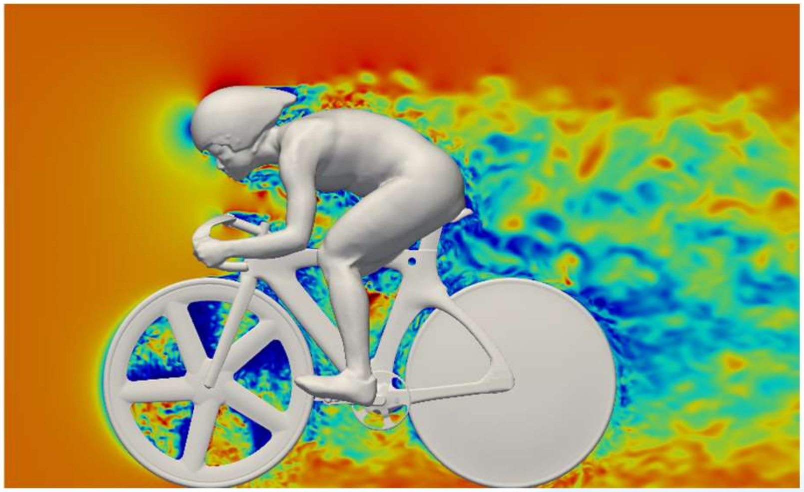


Red: high pressure region
Blue: low pressure region

Methods in cycling aerodynamics

- Testing in sports wind tunnels
- Simulation on high-performance computers

Research methods



Wind tunnel testing

Aero sports wind tunnel with various measurement systems

Numerical simulation

Computational fluid dynamics (CFD) simulation on supercomputers

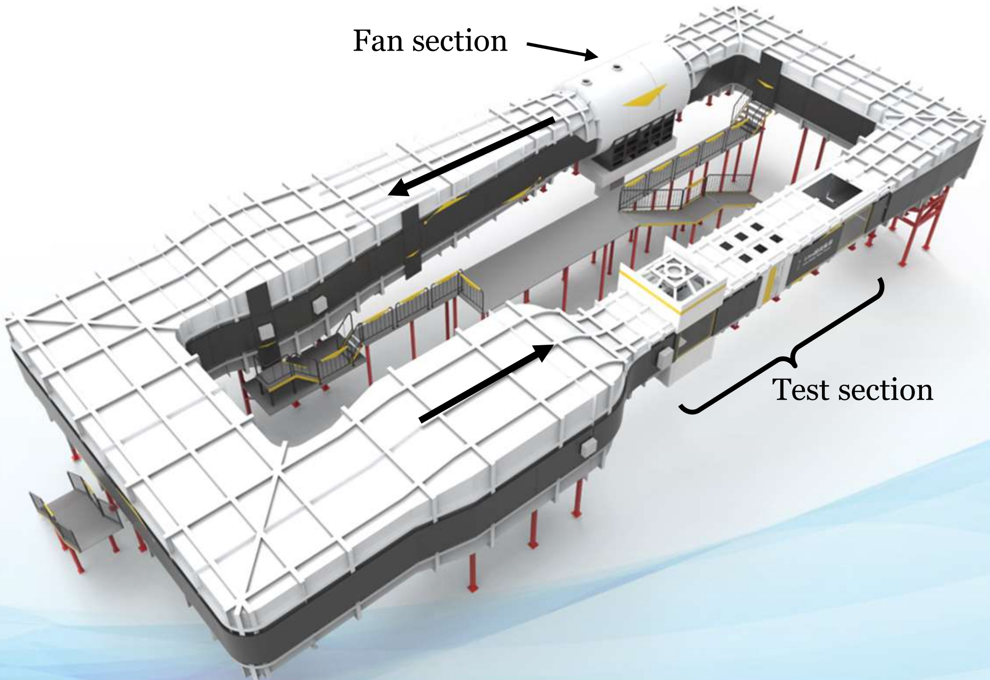
Development of a cycling mannequin

3D printed mannequin
(Wind tunnel testing)

3D model building
(Numerical simulation)

Experimental facilities

- Aero sports low-noise wind tunnel
- Aerodynamic bike test platform



- Test section (L * W * H):
  - $14\,m * 2.5\,m * 2\,m$
- High-quality flow
  - Flow uniformity: $\leq 0.5\%$
  - Flow angularity: $\leq 0.5^{\circ}$
  - Turbulence intensity: $\leq 0.12\%$

Wind tunnel tests on cyclists

🚴 Methodology

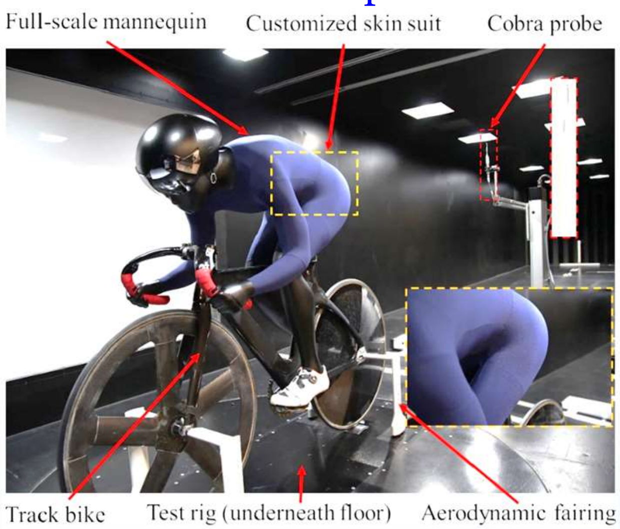
- Posture improvement : real track/road cyclist
- Equipment optimization: full-scale dummy cyclist, or static mannequin

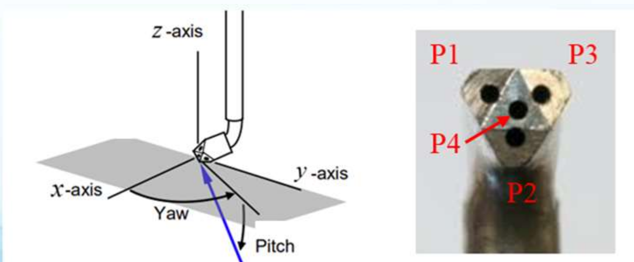
Real cyclist

Cycling mannequin

Measurement technology

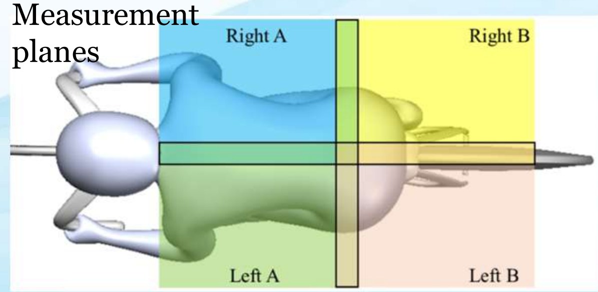
Wake velocity measurements by a multi-hole probe





Flow field measurements by particle image velocimetry (PIV)

Measurement planes



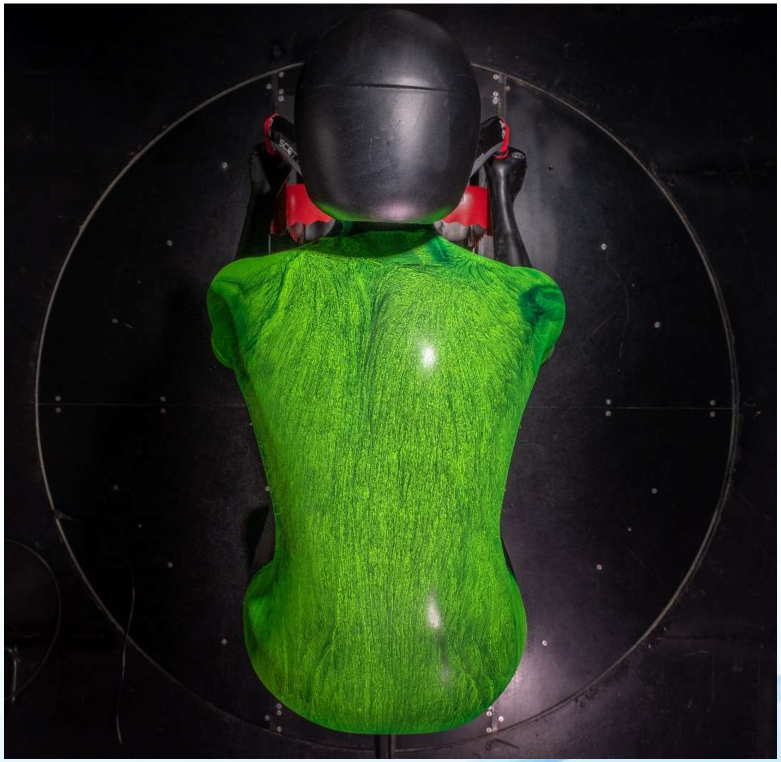
Flow visualisation

- Surface oil flow visualisation on a full-scale mannequin

Side view of the mannequin

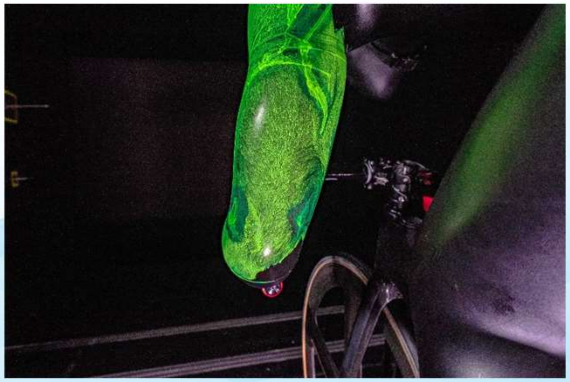
Close view of the left arm

Flow visualisation



Top view of the mannequin

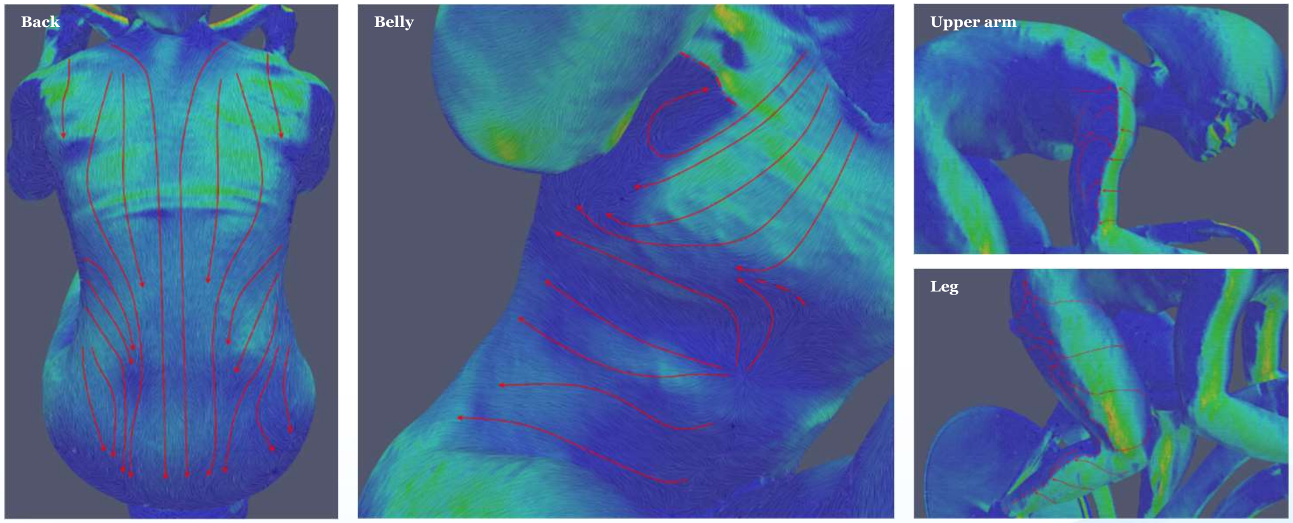
Side view of the mannequin



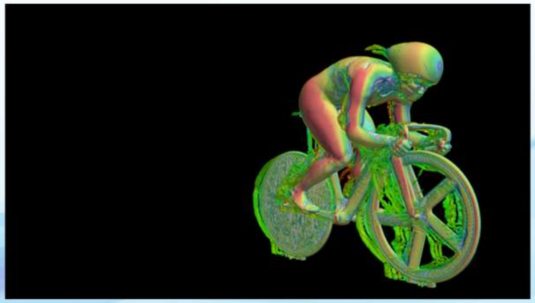
Rear view of the left arm

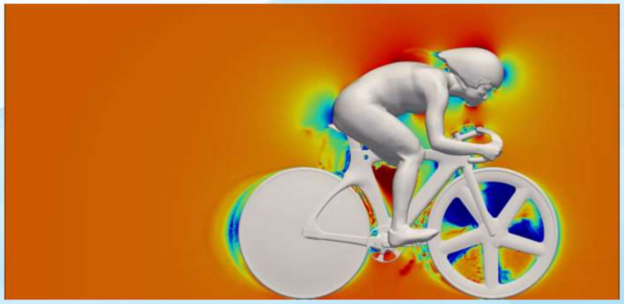
Single cyclist-bicycle CFD

- Flow topology on the surface of the cyclist's body at 18 m/s.

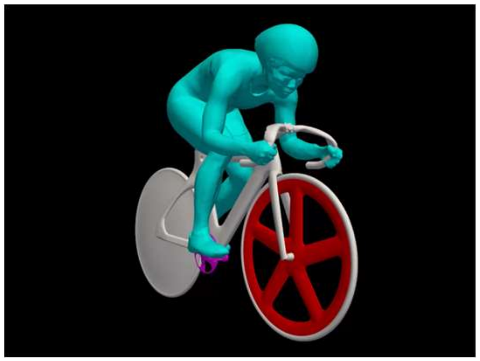


- Unsteady flow structures

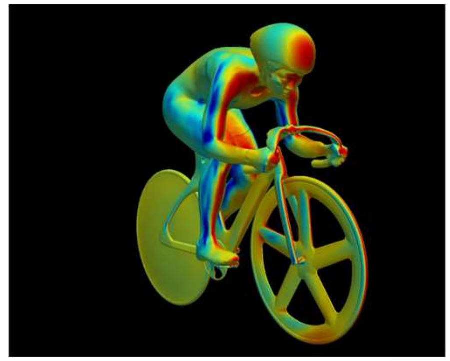




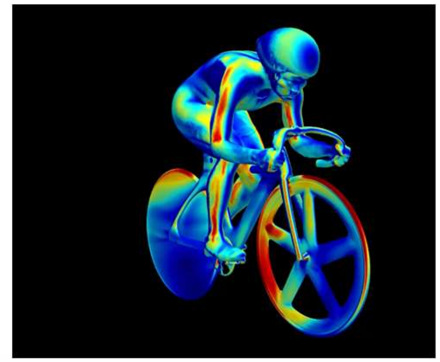
Single cyclist-bicycle CFD



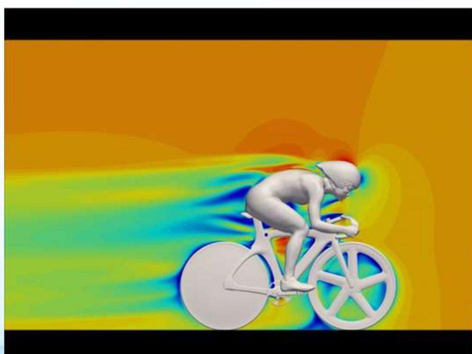
Postures



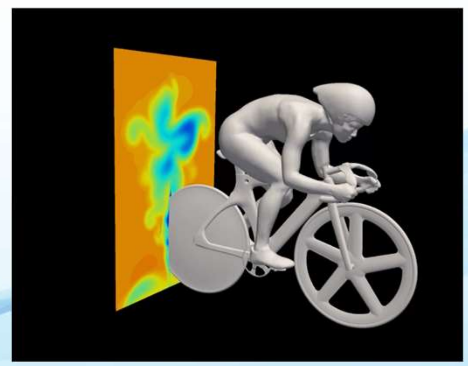
Surface pressure



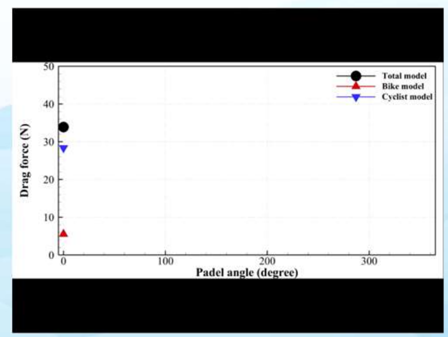
Surface wall shear stress (WSS)



Slice velocity



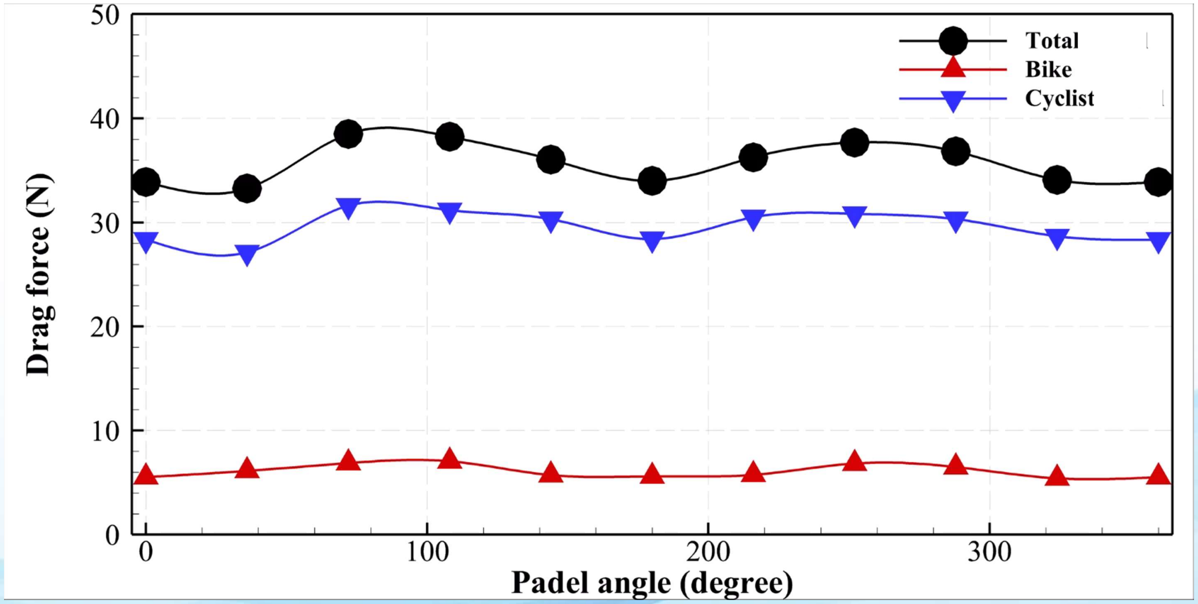
Slice velocity

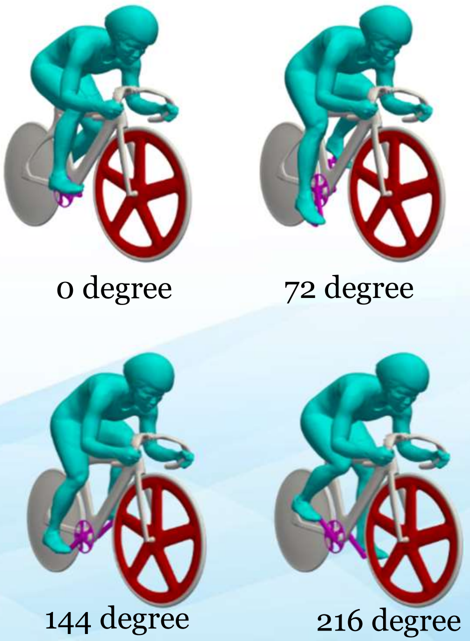


Drag force of whole model,
bicycle model and cyclist model

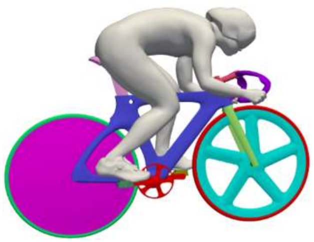
Effect of crank angle

- Effect of pedaling positions on the aerodynamic drag at 18 m/s.
  - The drag force experienced by the cyclist model is much higher than the bicycle part.
  - Minimum drag occurs around a horizontal crank position.



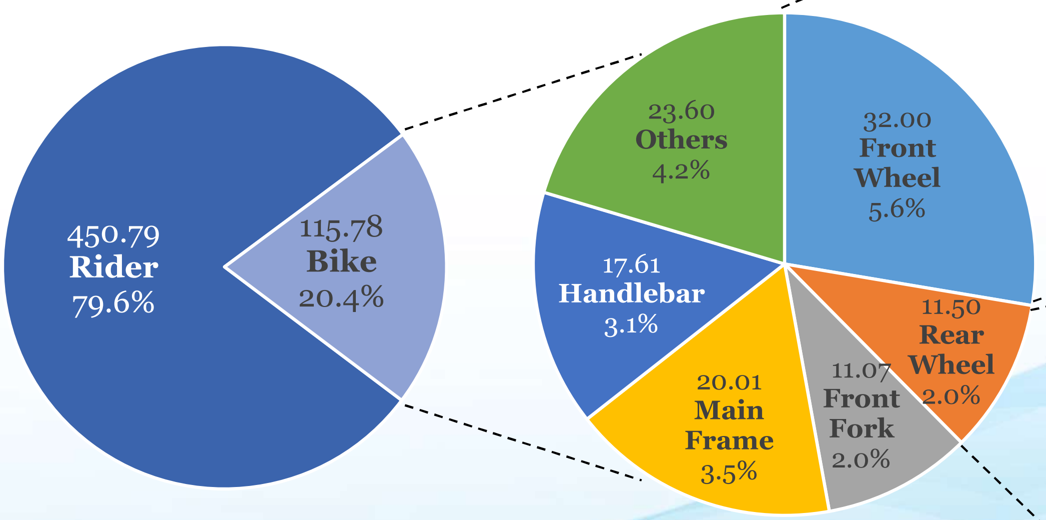


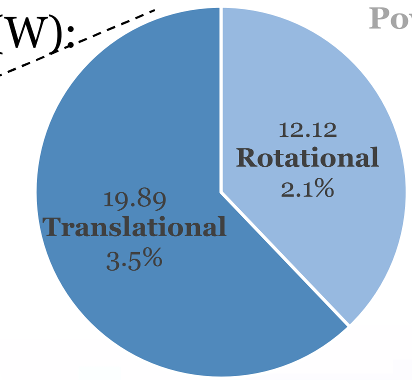
More insight from the CFD model

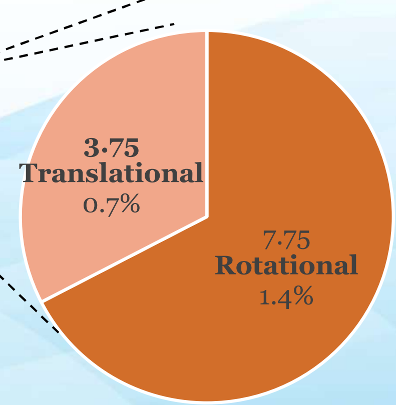


Aerodynamic power decomposition (W):

Notation:
Power in Watt
Power component
Percentage







The roles of aerodynamics

- Athlete posture optimization
- Equipment design & optimization
- Racing strategy

Aerodynamics for athlete posture optimization

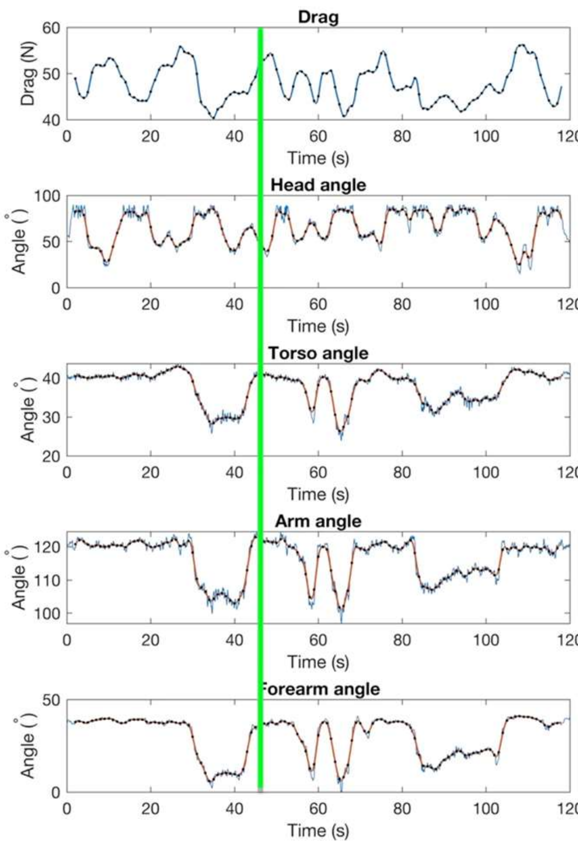
Athlete posture optimization

- Target: to achieve an optimum between low aerodynamic drag and high-power output capability with low physiological stress.

- Key procedures:
  - Investigate the sensitivity of drag on various posture parameters;
  - Test and refine the posture under high-power conditions;

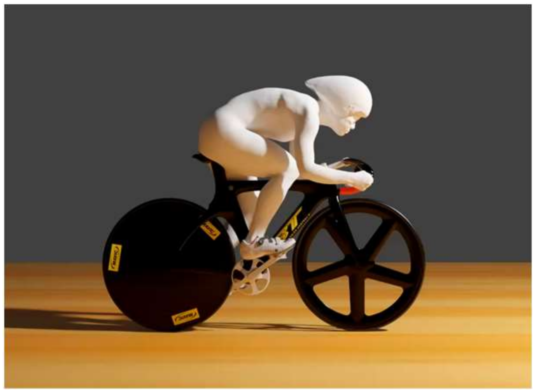
- Tools:
  - Video-based cyclist posture acquisition method (for posture parameters);
  - Simultaneous measurements for cross-correlation.

Drag-posture relation

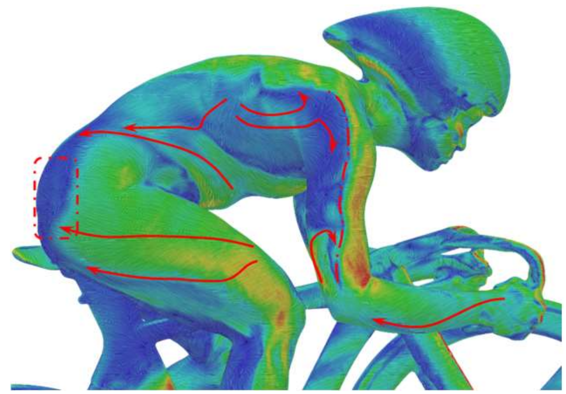


Aerodynamics for equipment design & optimization

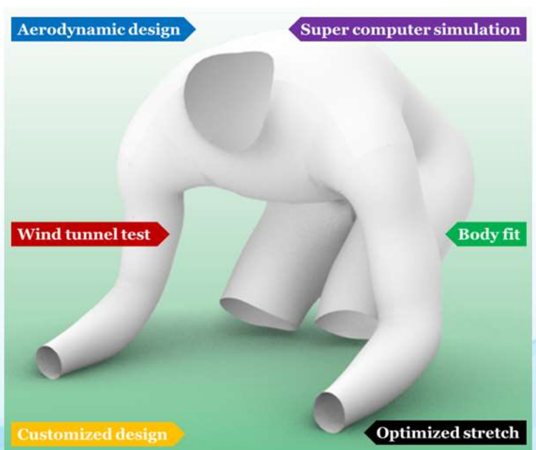
Low-drag skinsuit design



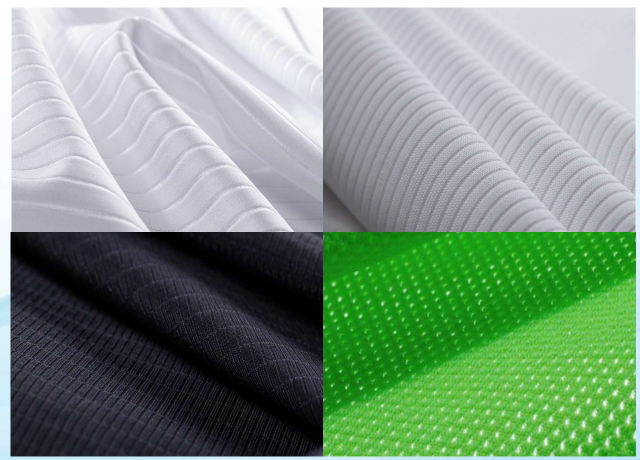
3D reconstruction



High-fidelity numerical simulation

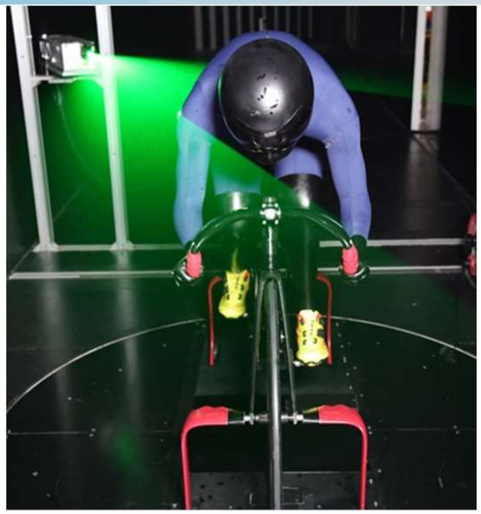


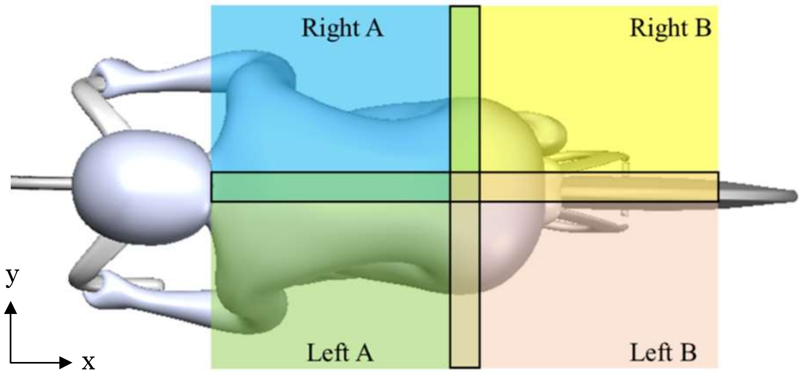
Design criteria

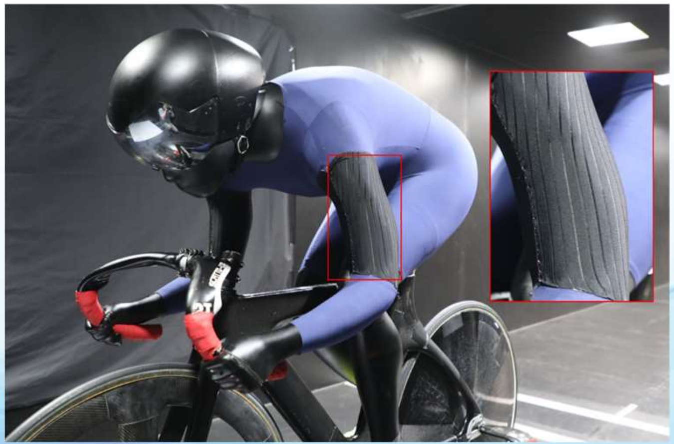


Fabric selection

Effect of fabric

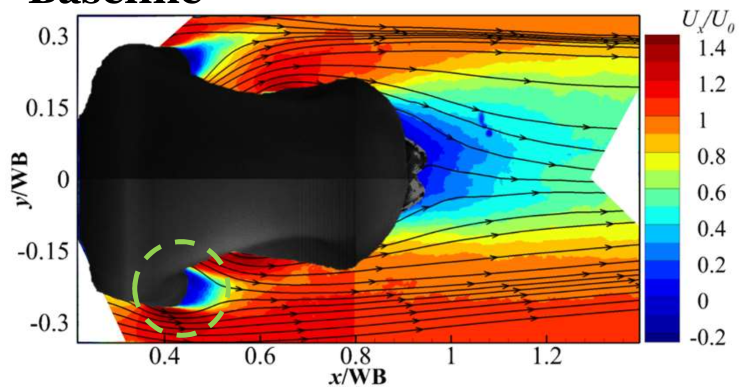




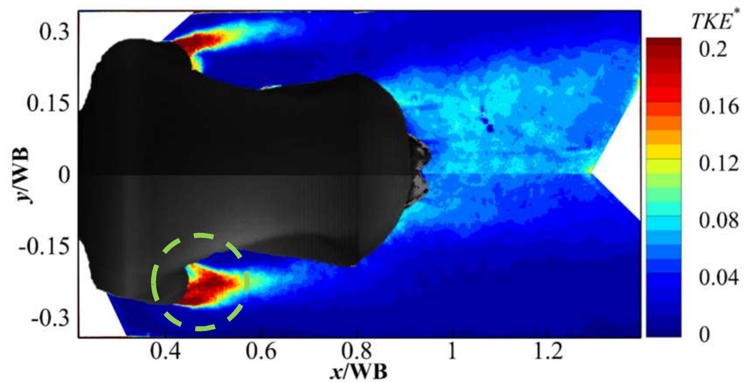


Effect of longitudinal groove fabric

Baseline

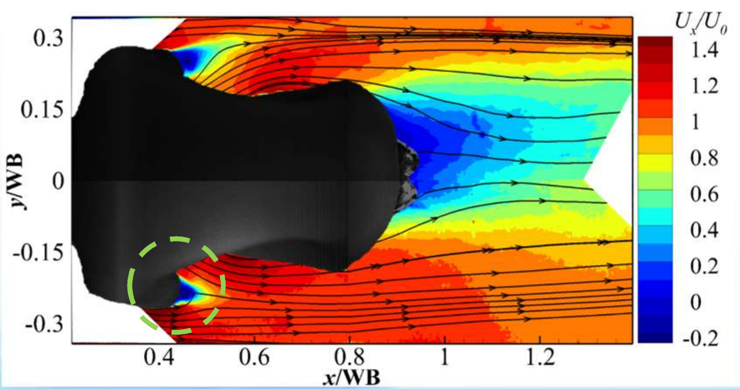


Streamwise velocity field

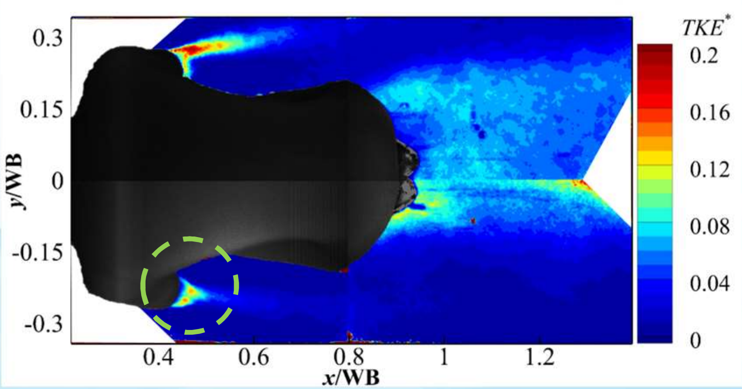


Turbulent kinetic energy distribution

fabric



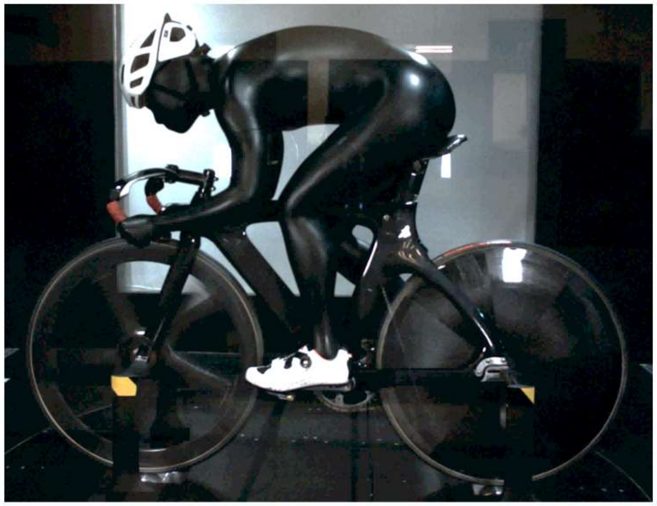
Streamwise velocity field



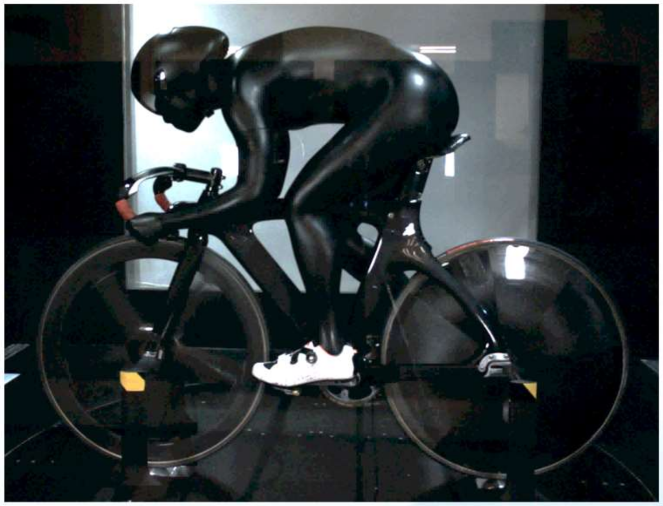
Turbulent kinetic energy distribution

Helmet performance analysis

Ordinary helmet



Aero. helmet



- Difference in $C_d A$: ~3.4%
- The difference is equivalent to:
  - 1.1% speed increment,
  - or 0.12 s time saving in a flying 200 m time trial (Ref: 11.00 s).

Effect of head angle

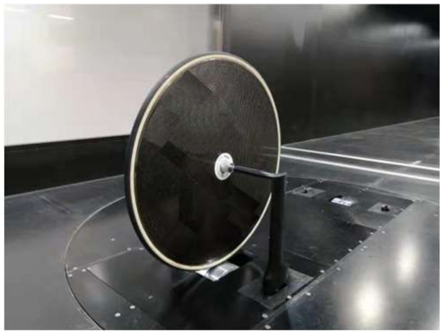
Head up | Head down

Helmet with a round tail

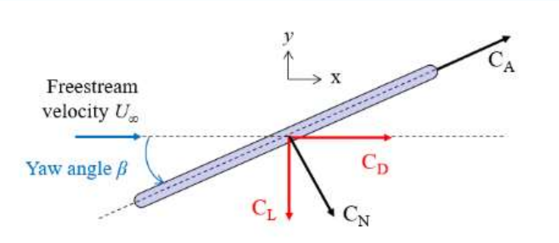
Helmet with a sharp tail

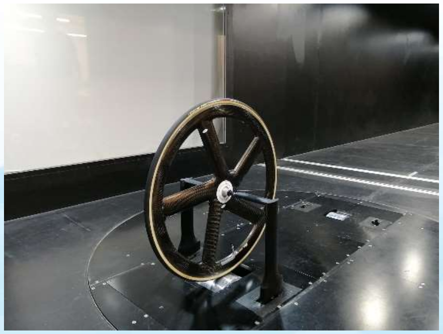
Wheel design and performance

- Aerodynamics of bicycle wheel
  - ~8% of the total power consumption
  - Manoeuvrability: side force, yaw moment
- Influential parameters
  - Rotational motion
  - Freestream air flow
  - Crosswind, or yaw angle
  - Wheel geometry



Disc wheel



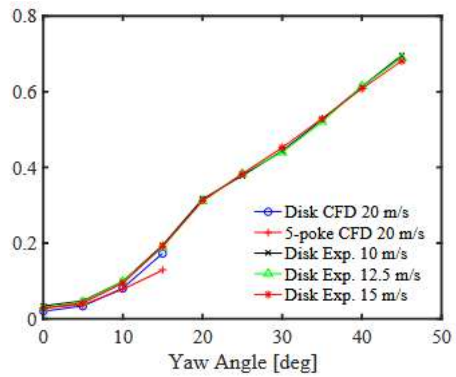


5-spoke wheel

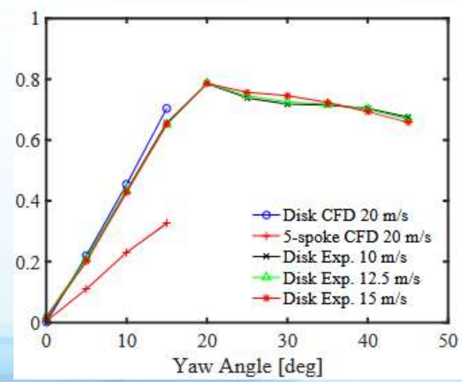
Yi, W., Bertin, C., Zhou, P., Mao, J., Zhong, S., Zhang, X., & So, R. (2022). Aerodynamics of isolated cycling wheels using wind tunnel tests and computational fluid dynamics., Journal of Wind Engineering & Industrial Aerodynamics, 228, 105085.

Effect of the yaw angle

Drag coefficient

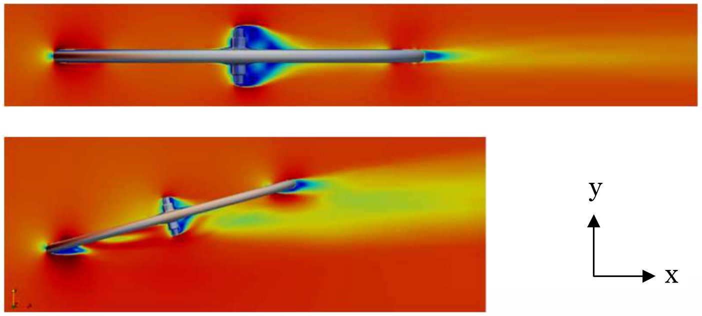


Lift coefficient

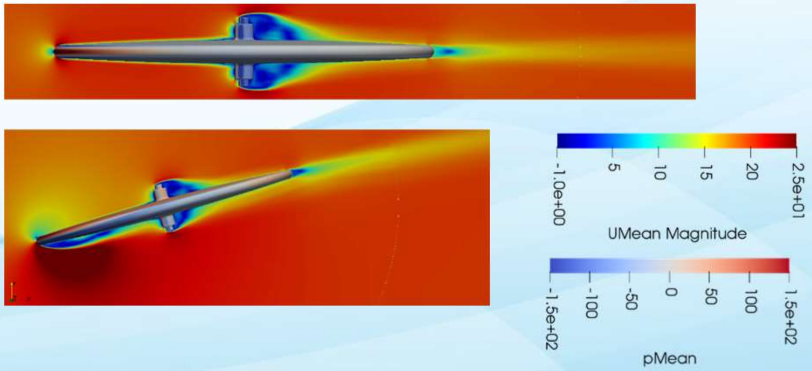


20 m/s at 0 ° and 15° yaw angle

5-spoke wheel top view



Disc wheel top view



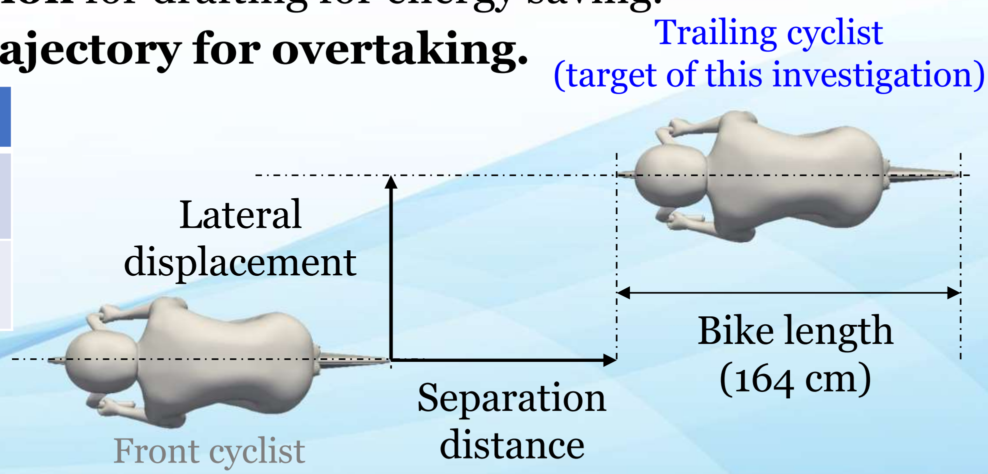
Aerodynamics for racing strategy

Motivation

- Drafting manoeuvre was widely adapted by cyclist both in indoor and outdoor races.
  - The drag of the trailing cyclist can be reduced.
- The benefit of drafting varies at different trailing positions.
  - Can be be investigated through CFD.
- The results can be used for:
  1. Choosing the **optimum position** for drafting for energy saving.
  2. Constructing the **optimum trajectory for overtaking.**

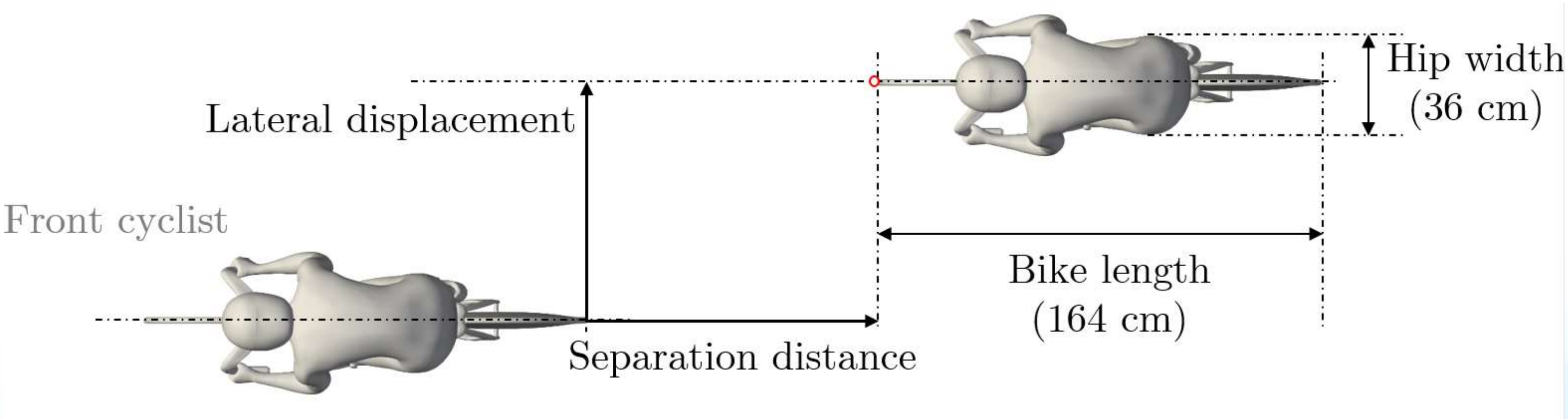
Parameters	Min	Max
Separation distance (Bike lengths)	0.145	3
Lateral displacement (Bike lengths)	0	0.94

Riding speed: 63 km/h (17.5 m/s)



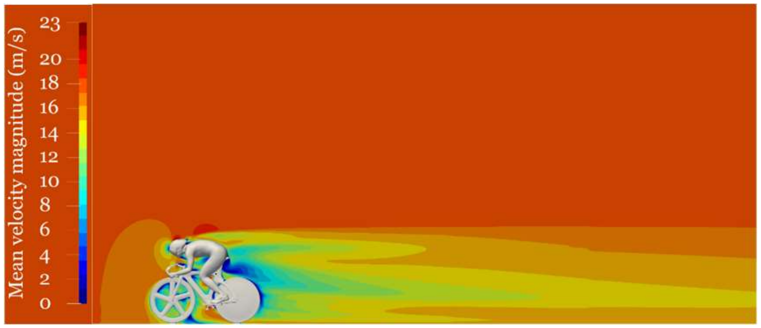
Dual-cyclist simulation

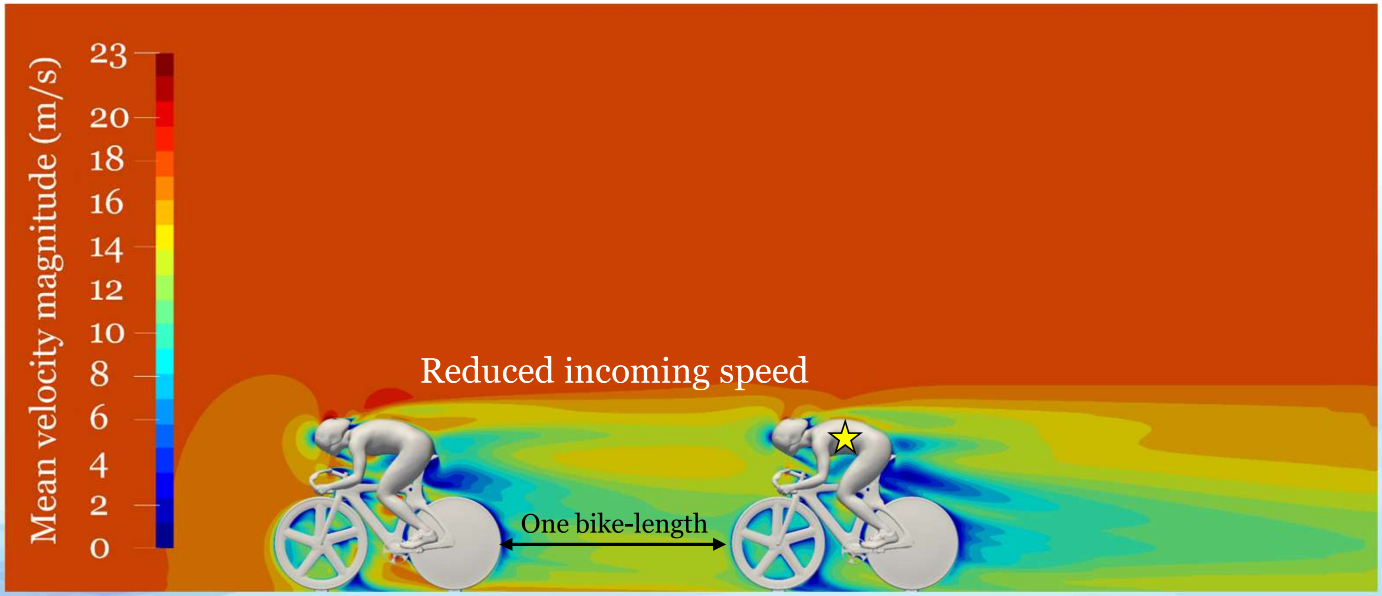
Numerical setup



- Number of cells: 80 – 110 millions.
- Number of time: 8 – 9 hours with 480 processors per case (Tianhe–2)

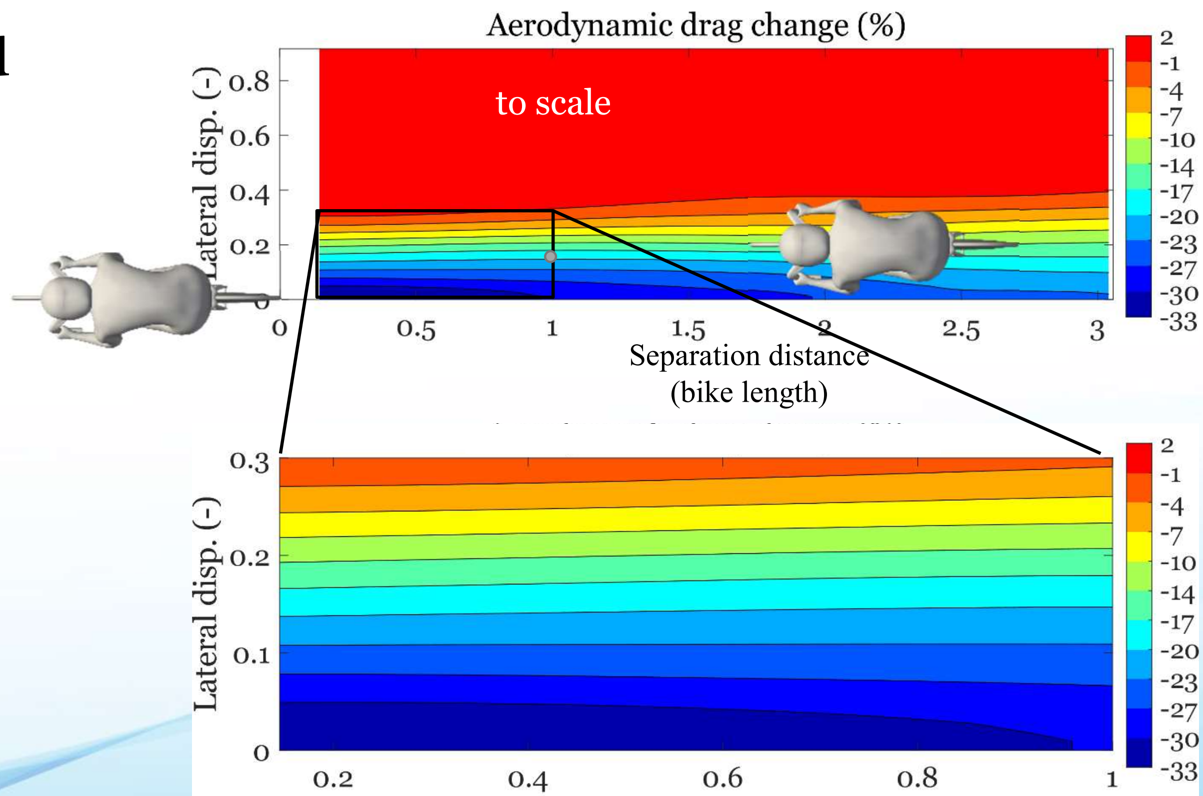
Mean velocity field around the cyclist(s)





Discussions

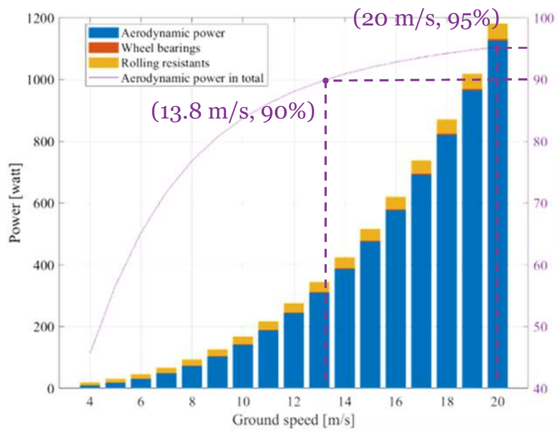
- Through drafting, drag could be reduced up to 33%.
  - Aerodynamic drag is more sensitive to the lateral displacement than separation distance.
  - Drag reduction is negligible if lateral displacement > 1 body width.
  - Significant drag reduction is achievable even for large separation distance.



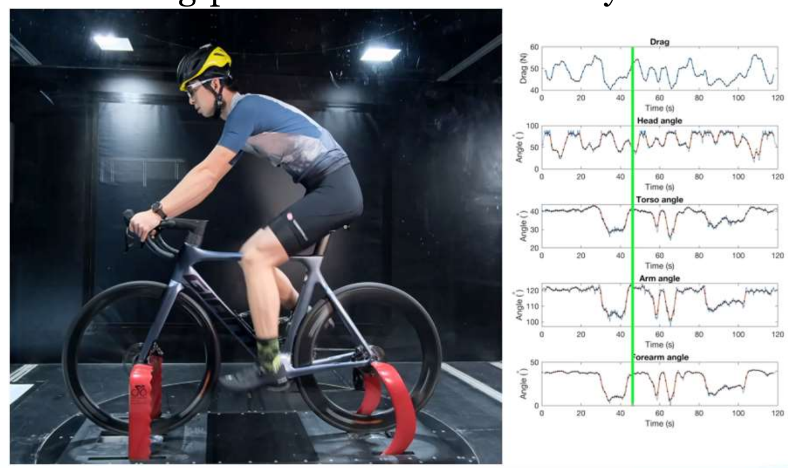
Summary

Summary

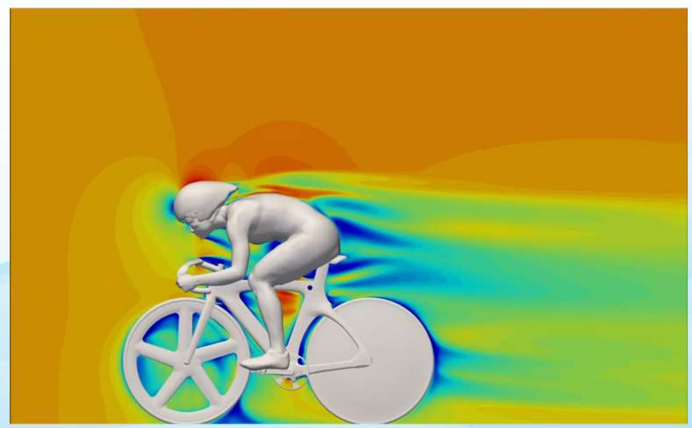
Power decomposition in cycling



Drag-posture relation for real cyclist



Equipment design and evaluation



Numerical simulation of the flow field

Acknowledgement

This work was supported by:

- A. Kwok sports aerodynamics science initiative;
- ITS/354/18FP: Development of key aerodynamic technologies to enhance cycling competition performance.

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The presentation was prepared with Prof. Peng Zhou and Mr. Jiaqi Mao.