Marginal Gains in Aerodynamics

Dr Nash Vracas

Who Am I?

Dr Nash Vracas, CEng
MPhys, MSc, PhD, MRAeS, MIoP

Automotive Sector:

- Aston Martin
- Jaguar Land Rover
- Gordon Murray
- ForSeven

Elite Sport:

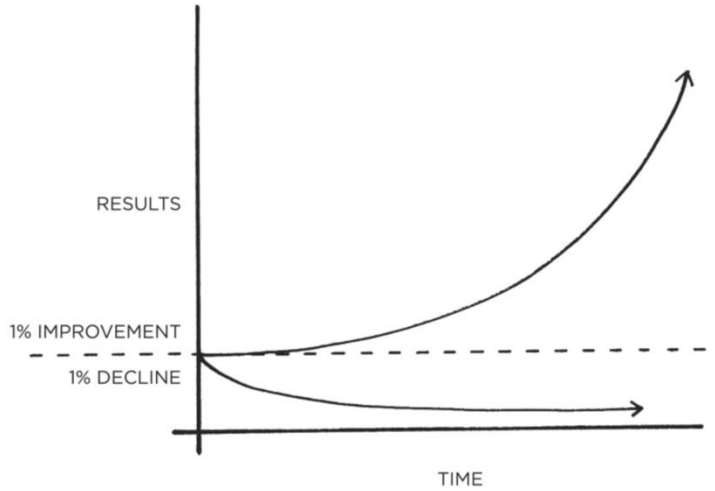
- British Skeleton
- British Rowing
- Elite Cycling

Chair and Trustee of the Greenpower Education Trust

Why Marginal Gains?

“The whole principle came from the idea that if you break down everything involved in riding a bike and improve each element by just 1%, the overall impact will be significant when you put them all back together.” – Sir David Brailsford

Why Marginal Gains?



Whilst the concept of marginal gains, or the 1% effect, was made famous by Brailsford, the ideology has roots in Kaizen (continuous improvement). Kaizen is a Japanese business philosophy used in manufacturing and management, initially by Toyota but now throughout the engineering sector. It aligns with principles from behavioural psychology and compounding effects, which emphasise how tiny daily improvements can lead to remarkable long-term results.

The marginal gains or the 1% effect is built on a simple yet powerful idea: small, consistent improvements compound over time, leading to exponential growth. Too often, we assume that achieving massive success requires equally massive actions. We put immense pressure on ourselves to make dramatic, noticeable changes, but real progress doesn't happen overnight. Instead, it's the small, incremental improvements—just 1% at a time—that create the biggest impact in the long run.

Dave Brailsford focussed on finding tiny improvements from bike weight to aerodynamics. But he didn't stop there, he found the most optimum nutrition to the best ways to wash your hands to reduce illness and found the best mattress that the athletes sleep on. Although these may seem insignificant in isolation, when you start to put them together, your tiny changes compound and you end up with significant changes overall. This is the 1% effect and what made British Cycling so famous. Brailsford went on to with multiple Tour de France, eight gold medals in the Beijing Olympics and turned BC into a household name.

What is Aerodynamics?

We resolve the fluid behaviour into the normal and tangential components:

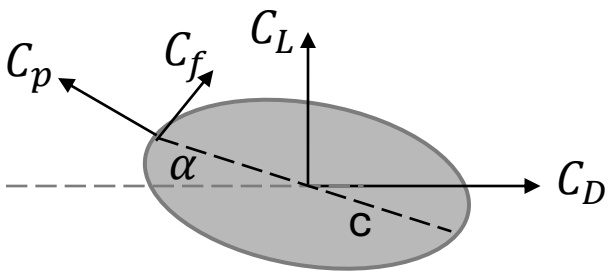
$$C_p = \frac{p - p_\infty}{q_\infty}$$ Pressure coefficient → shape of the body

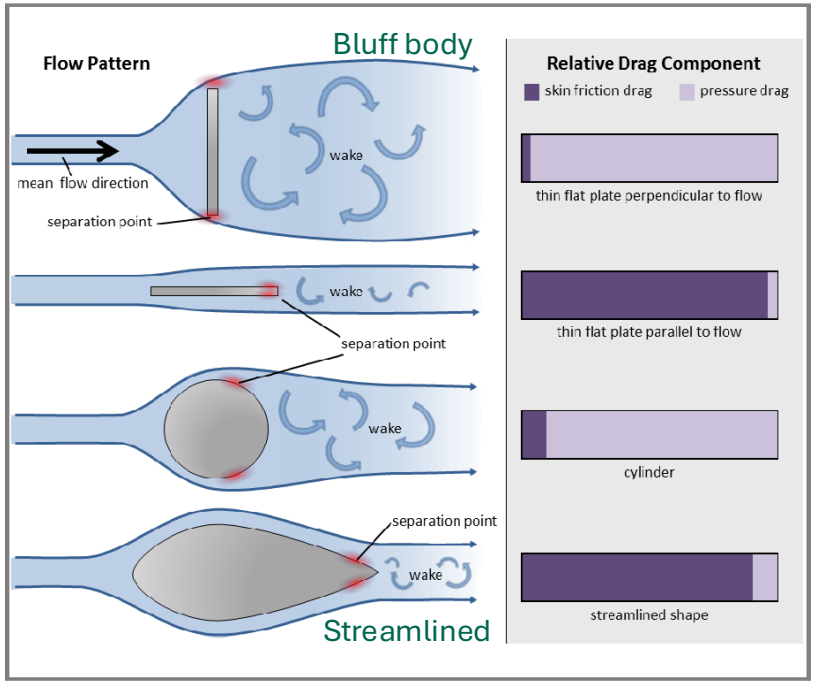
$$C_f = \frac{\tau}{q_\infty}$$ Skin friction coefficient → effect of the surface

Drag coefficient:

$$C_D = \frac{1}{c}\left[\int_0^c (C_{p,l} - C_{p,u})dx + \int_0^c \left(C_{f,u}\frac{dy_u}{dx} - C_{f,l}\frac{dy_l}{dx}\right)dx\right] cos\alpha - \frac{1}{c}\left[\int_0^c \left(C_{p,u}\frac{dy_u}{dx} - C_{p,l}\frac{dy_l}{dx}\right)dx + \int_0^c (C_{f,u} + C_{f,l})dx\right] sin\alpha$$

$$C_L = \frac{1}{c}\left[\int_0^c (C_{p,l} - C_{p,u})dx + \int_0^c \left(C_{f,u}\frac{dy_u}{dx} - C_{f,l}\frac{dy_l}{dx}\right)dx\right] sin\alpha - \frac{1}{c}\left[\int_0^c \left(C_{p,u}\frac{dy_u}{dx} - C_{p,l}\frac{dy_l}{dx}\right)dx + \int_0^c (C_{f,u} + C_{f,l})dx\right] cos\alpha$$



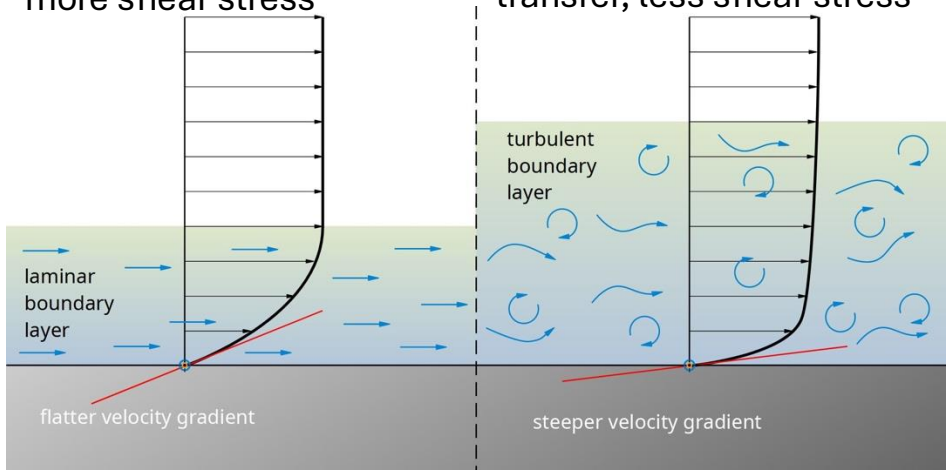


What is Aerodynamics?

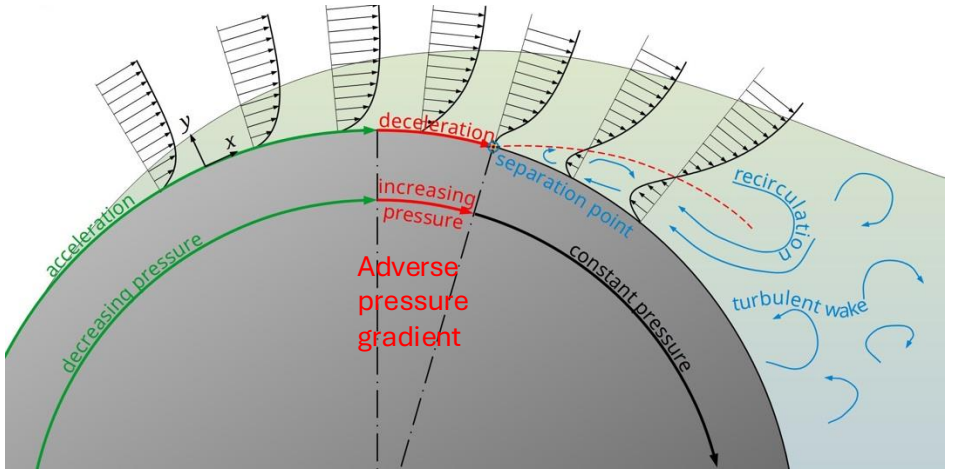
Boundary Layer: region where flow goes from 0m/s to freestream

Less momentum transfer, more shear stress

More momentum transfer, less shear stress

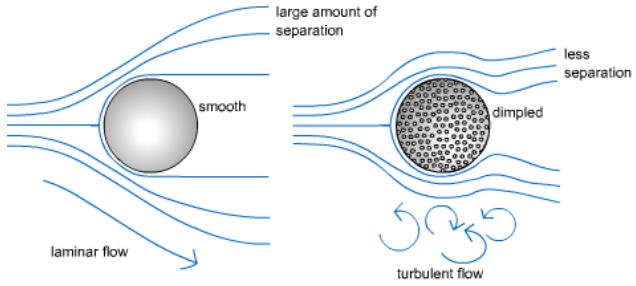


Separation occurs when the velocity gradient is zero



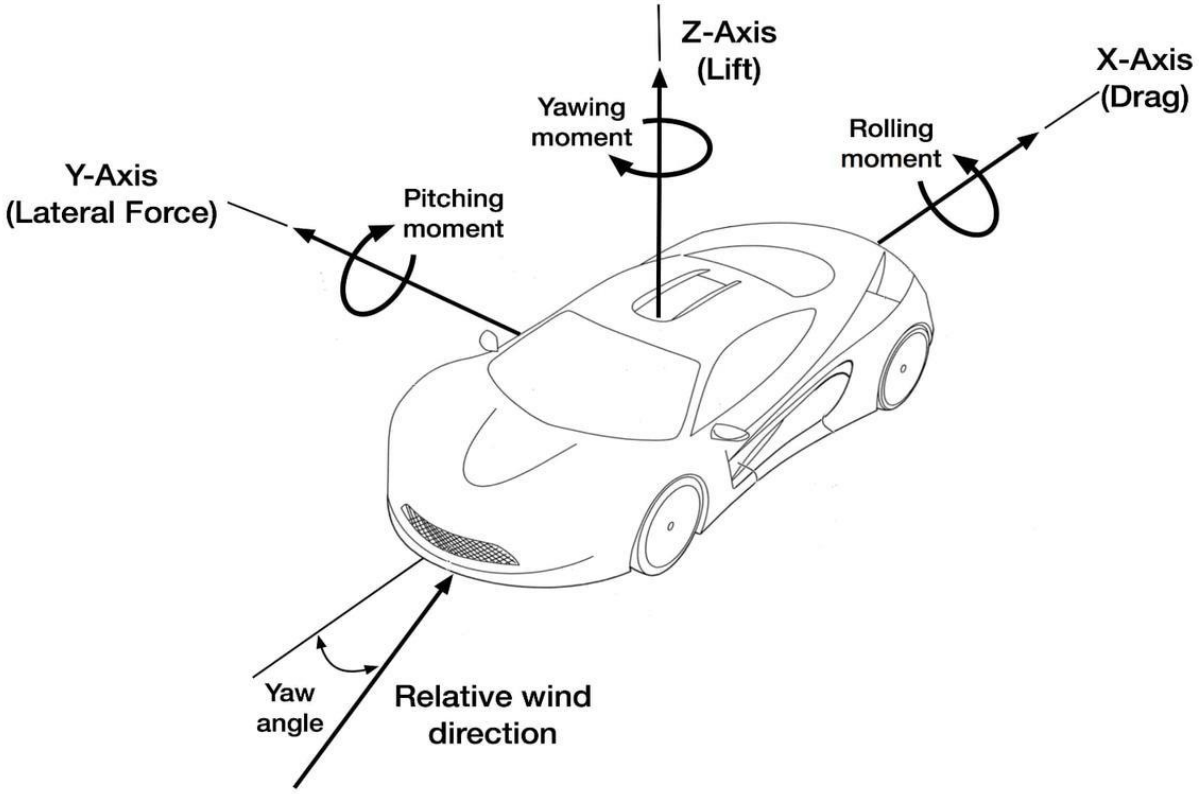
A turbulent boundary layer can be beneficial as it delays the separation point.

The most famous example is dimples on a golf ball.
They trip a laminar BL into a turbulent BL, which delays separation point, reducing the wake size and reducing the overall drag.



What is Aerodynamics?

Ok but what about the forces?



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

$$L = \frac{1}{2}\rho v^2 C_L A$$

$$S = \frac{1}{2}\rho v^2 C_S A$$

Drag coefficient C_D
Frontal area A

Integrated Systems

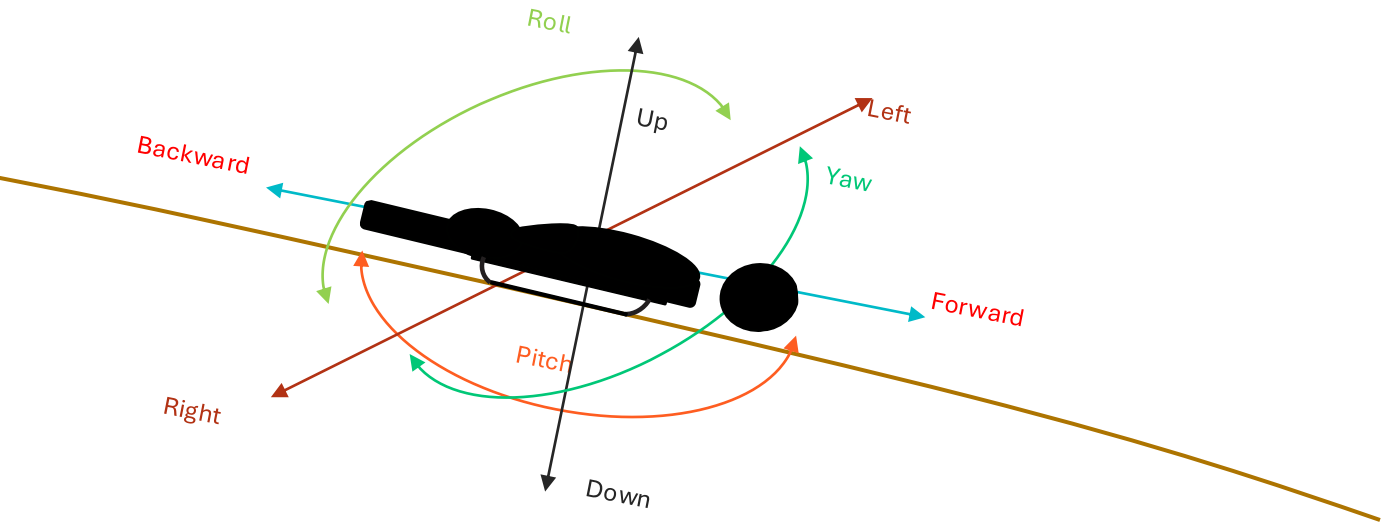
Integrated systems are essential because they provide a holistic view, ensuring that development leads to a genuine net improvement. Optimising components in isolation can result in unintended consequences—potentially degrading overall system performance rather than enhancing it.

We are going to use the sport of Skeleton as an example:

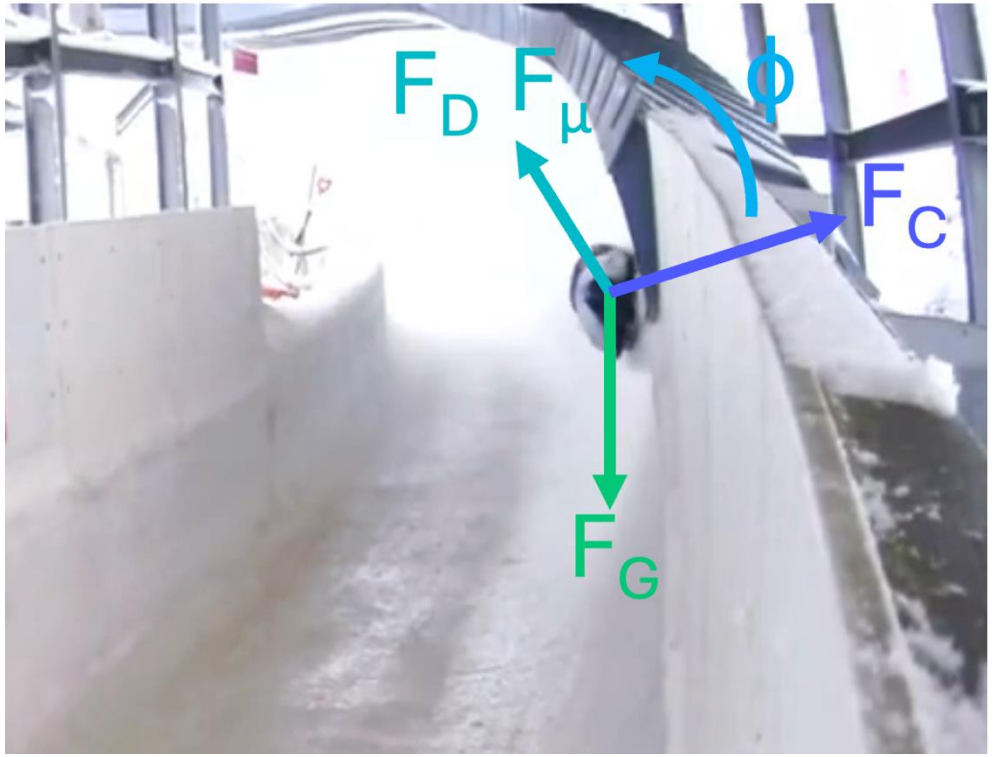
Skeleton is a winter sliding sport. It originated in St. Mortiz, Switzerland, where athletes slide head first down an ice track. It is often described as Formula 1 on ice because the athletes experiences speeds up to 140kph (~90mph) and up to 5G.

Competitions are held across Europe, Germany, France, Latvia, Switzerland, as well as in NA (Canada and US), Russia, Korea and most recently in China!

Skeleton has 6DoF, three linear and three angular.



An example in a circular section of the track:



To analyse the holistic system, we need to be able to understand each aspect of the system and it's application.

In n=3 Real Space, the 6DoF motion is given by:

$$\mathbf{x}_3^{[1]} = \mathbf{F}_0\mathbf{x}_3^{[2]} + \mathbf{G}_0\mathbf{u}_3^{[1]}$$

Linear

$$\mathbf{x}_3^{[1]} = \begin{bmatrix} \mathbf{x}_1^{[1]} \\ \hline \mathbf{x}_2^{[1]} \end{bmatrix} = \begin{bmatrix} \dot{\mathbf{u}} \\ \dot{\mathbf{v}} \\ \dot{\mathbf{w}} \\ \hline \dot{\mathbf{p}} \\ \dot{\mathbf{q}} \\ \dot{\mathbf{r}} \end{bmatrix}$$

$$\mathbf{u}_3^{[1]} = \begin{bmatrix} \mathbf{u}_1^{[1]} \\ \hline \mathbf{u}_2^{[1]} \end{bmatrix} = \begin{bmatrix} \tilde{\mathbf{F}}_x \\ \tilde{\mathbf{F}}_y \\ \tilde{\mathbf{F}}_z \\ \hline \mathbf{L} \\ \mathbf{M} \\ \mathbf{N} \end{bmatrix}$$

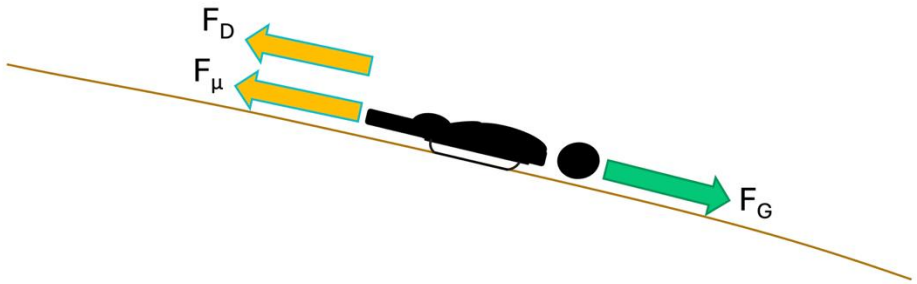
$$\mathbf{G}_0 = \begin{bmatrix} \mathbf{I} & \mathbf{0} \\ \hline \mathbf{0} & \mathbf{A}_0^{-1} \end{bmatrix}$$

Angular

$$\mathbf{x}_3^{[2]} = \begin{bmatrix} \mathbf{x}_1^{[2]} \\ \hline \mathbf{x}_2^{[2]} \end{bmatrix} = \begin{bmatrix} \mathbf{uq} \\ \mathbf{ur} \\ \mathbf{vp} \\ \mathbf{vr} \\ \mathbf{wp} \\ \mathbf{wq} \\ \hline \mathbf{p^2} \\ \mathbf{pq} \\ \mathbf{pr} \\ \mathbf{q^2} \\ \mathbf{qr} \\ \mathbf{r^2} \end{bmatrix}$$

$$\mathbf{F}_0 = \begin{bmatrix} \mathbf{C}_0 & \mathbf{0} \\ \hline \mathbf{0} & \mathbf{A}_0^{-1}\mathbf{B}_0 \end{bmatrix}$$

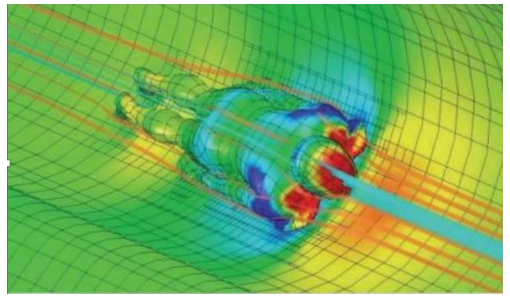
The 1D system is given by:



$$F_{Total} = F_{gravity} - F_{friction} - F_{drag}$$

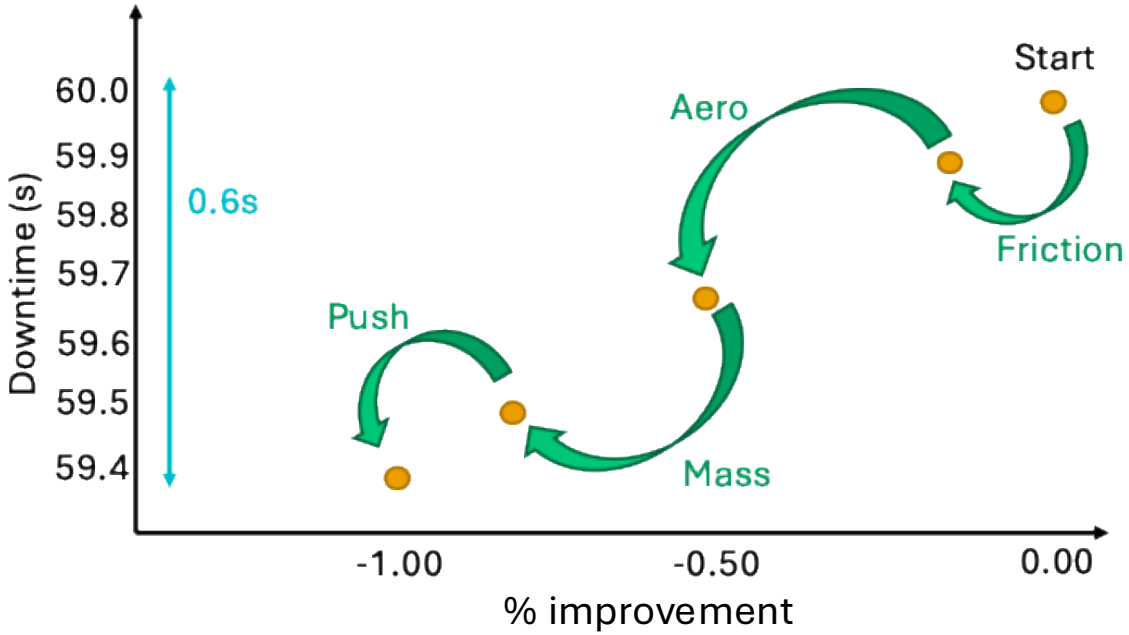
Optimising the System:

Aerodynamics is optimised through CFD (computational fluid dynamics) and wind tunnel testing of both the equipment and athlete body position.



Friction is optimised through runner design. This is the same as tyre choice in motorsport. You wouldn't want an off-road tyre in F1 as it would give far too much friction!

If we take an example and improve the performance of each component:



Whilst 0.6s may only seem like a small amount, it can be the difference between gold and bronze.

G		Lizzy Yarnold	3:27:28	
S		Jacqueline Loelling	3:27:73	+0:00:45
B		Laura Deas	3:27:90	+0:00:62
4		Janine Flock	3:27:92	+0:00:64

+0:00:02

‘*The plan was to leave no stone unturned in our attention to detail, which unfolded over months and years of planning and execution across a whole team of people. What an immense privilege (and pressure) it was to stand on the start line knowing how much work had gone into putting me in that position – all that was left was to go out there and do what I knew I was capable of.*’ - Laura Deas

An Example: Cycling

Understanding Aerodynamics in Cycling

Once a cyclist exceeds ~15 km/h, aerodynamic drag becomes the dominant force resisting motion. At race speeds (40–50 km/h), drag can account for up to 90% of total resistance.

Drag increases with the square of speed; power required increases with the cube. Small reductions in drag can yield significant performance gains.

Two main factors influence aerodynamic performance:

1. The rider – Body position, clothing and helmet shape airflow. Tight, textured skinsuits and tucked positions minimise drag.

2. The bike – Frame design, wheels and integration of components all matter. Teams use wind tunnels, CFD and real-time sensors to optimise setups.

Even minor details: e.g. bottle placement, cable routing and bar tape texture can make a measurable difference.

Major gains often come not from dramatic redesigns but from incremental, data-driven improvements. This is the principle of marginal gains in action.

An Example: Cycling

80% of the resistance comes from aerodynamics

- 60% comes from the rider (position and clothing)
  - 30% comes from the clothing

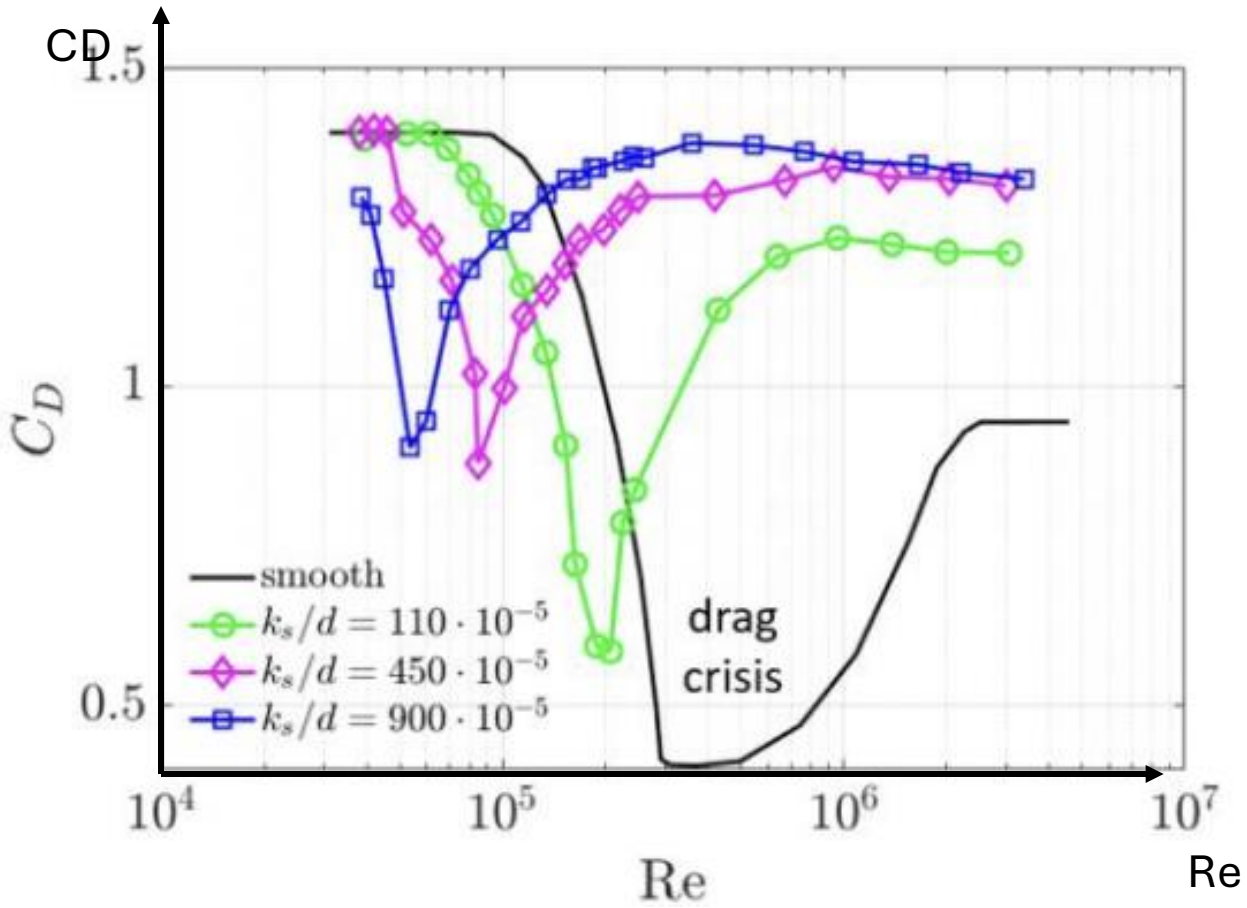
10% reduction in drag of the suits can result in a 60s reduction over a 40km time trial

An Example: Cycling

Aerodynamics of Cycling Apparel

- Wearing a skinsuit instead of standard cycling kit can reduce drag by up to 30%.
- Simply choosing long sleeves over short sleeves offers an additional 11% reduction.
- Most high-performance cycling clothing is made from knitted fabrics, which stretch to fit tightly around the body, reducing loose material and air resistance.
- Interestingly, stretching these fabrics increases surface roughness, which can actually improve airflow at race speeds by delaying flow separation.
- Even minor material tweaks matter:
  - A small change in Lycra manufacturing resulted in 0.1–0.9% drag improvements

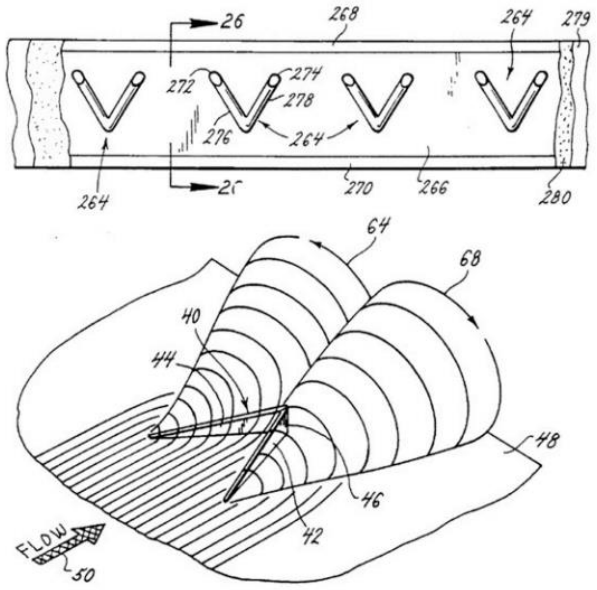
An Example: Cycling



The body is broken up into zones and fabric is chosen to have the lowest drag in each one.

An Example: Cycling

Vortex Generators



Vortex Generators, or small ridges, on fabrics can control airflow effectively without causing the post-critical drag increase. However, some tests have shown they can increase drag up to 25% and are now banned in most competitions.

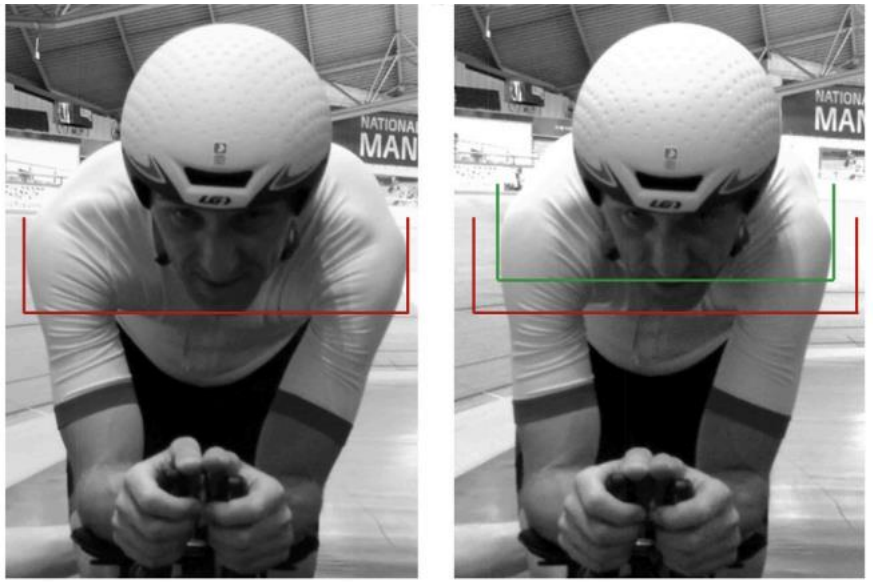
Double Layered Fabrics

An alternative is double layered structures that have seen a 1-2% improvement in performance.

An Example: Cycling

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

Both have C_D = 0.38



Drag area reduced by 3.5%

- Another key factor to performance is frontal area.
- Small changes in frontal area will also affect the airflow over the body.
- It is important to have an overall benefit, which is why is sport you'll often hear the 'drag area' being referred to.

An Example: Cycling

Position "Top tube 4"

$C_DA = 0.201\ m^2$

[ref.]

Position "Pantani"

$C_DA = 0.212\ m^2$

+5.5%

Position "Back horizontal"

$C_DA = 0.236\ m^2$

+17.4%

Position "Back down 2"

$C_DA = 0.214\ m^2$

+6.5%

Position "Froome"

$C_DA = 0.233\ m^2$

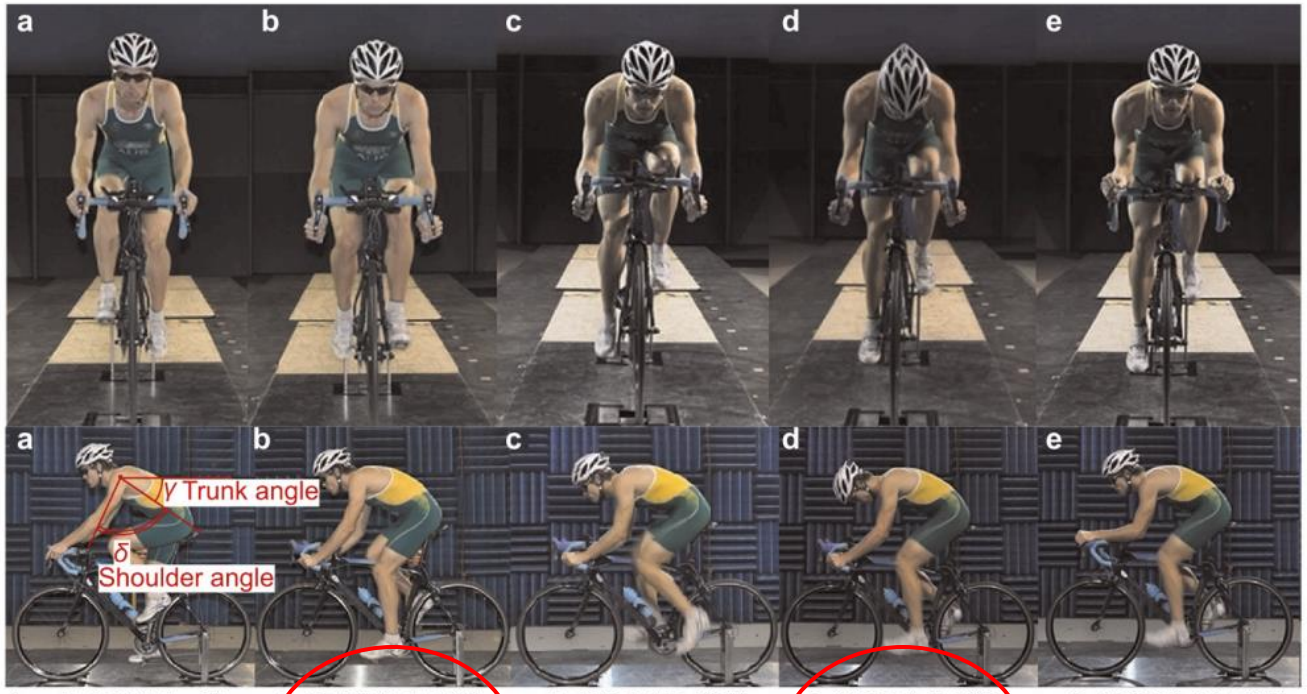
+15.9%

Position "Superman"

$C_DA = 0.150\ m^2$

-25%

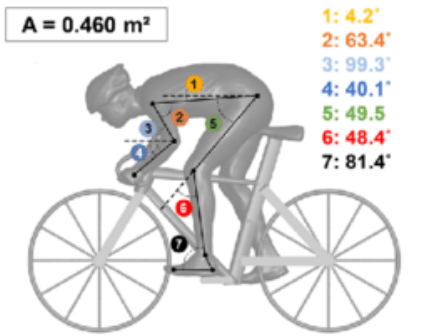
An Example: Cycling



A = 0.4941 (ref.)	0.4720 (-4.5%)	0.4594 (-7.0%)	0.4520 (-8.5%)	0.4365 (-11.7%)
C_D = 0.6942 (ref.)	0.7034 (+1.3%)	0.6661 (-4.0%)	0.7102 (+2.3%)	0.6758 (-2.6%)
C_DA = 0.343 (ref.)	0.332 (-3.2%)	0.306 (-10.8%)	0.321 (-6.4%)	0.295 (-14.0%)

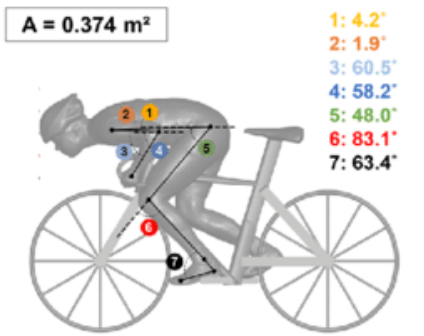
An Example: Cycling

a **Position "Sprint regular"**



$A = 0.460 m^2$
$C_D = 0.670$
$C_D A = 0.308 m^2$

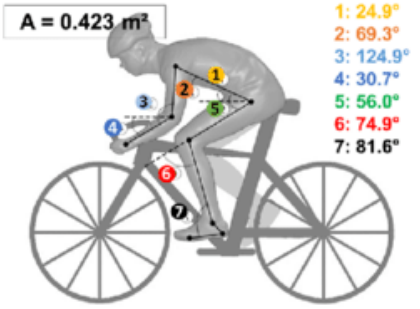
b **Position "Sprint low"**



$A = 0.374 m^2$ (-19%)
$C_D = 0.626$ (-7%)
$C_D A = 0.234 m^2$ (-24%)

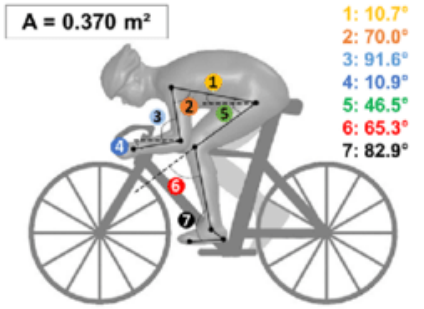
1: sagittal torso angle
2: shoulder angle
3: elbow angle
4: forearm angle
5: hip angle
6: knee angle
7: ankle angle

c **Position "Back upwards"**



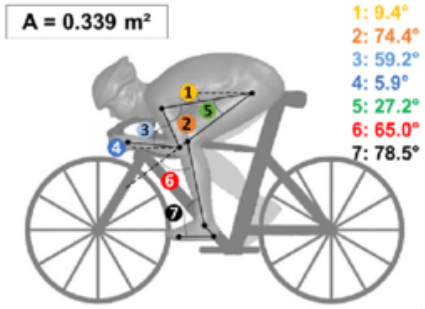
$A = 0.423 m^2$ (-8%)
$C_D = 0.655$ (-2%)
$C_D A = 0.277 m^2$ (-10%)

d **Position "Back horizontal"**



$A = 0.370 m^2$ (-20%)
$C_D = 0.638$ (-15%)
$C_D A = 0.236 m^2$ (-23%)

e **Position "Back down"**



$A = 0.339 m^2$ (-26%)
$C_D = 0.655$ (-2%)
$C_D A = 0.222 m^2$ (-28%)

An Example: Automotive

•Much of today's focus has been on sport, largely because of the abundance of publicly available data.

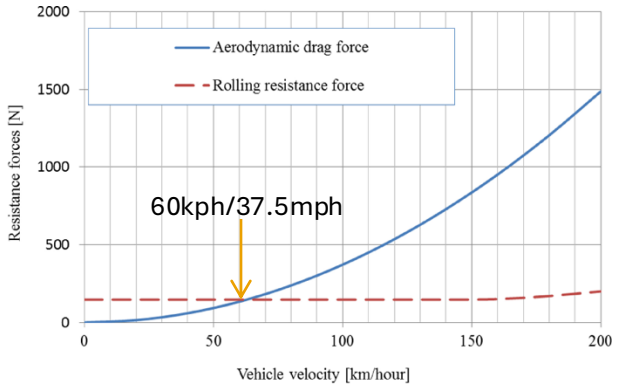
•In contrast, many non-sport applications, particularly in industry, are subject to strict NDAs, limiting what can be shared.

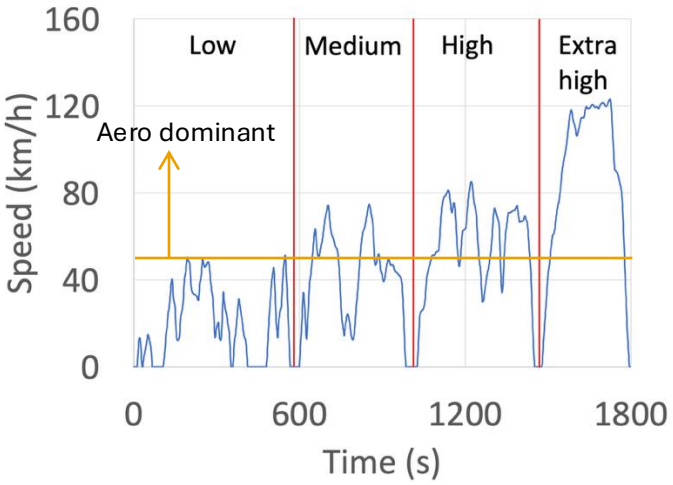
•One example that can be discussed is the Range Rover, which achieved the lowest drag coefficient of any luxury SUV.

•This was made possible by applying the same marginal gains approach used in elite sport, targeting small, incremental improvements across the entire system.

•Further technical detail is available in a recent SAE publication, written by Adrian Gaylard, which outlines the aerodynamic development process.

An Example: Automotive



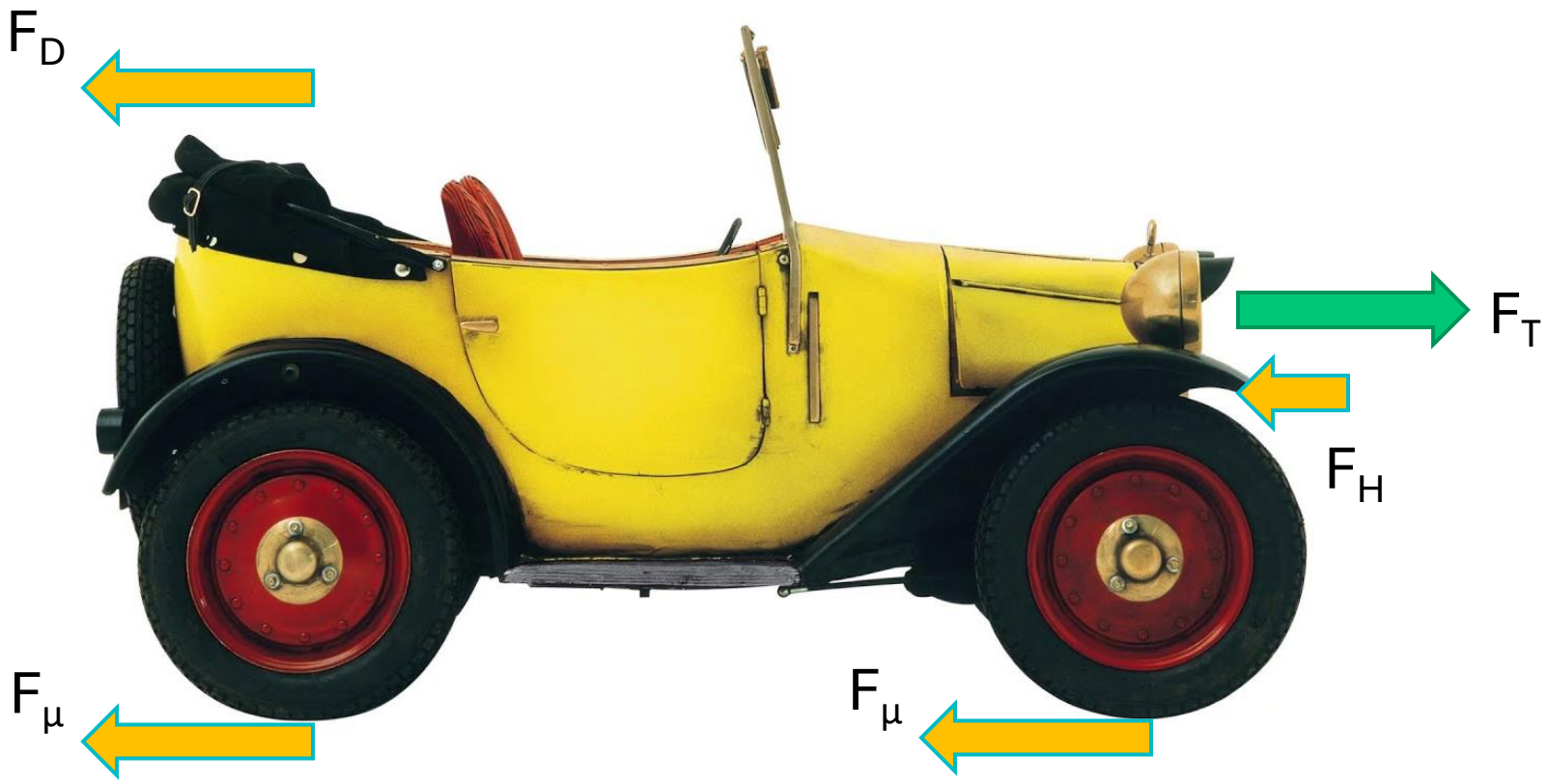


- Aerodynamic drag has a quadratic relationship with velocity
- At low speeds:
  - Rolling resistance/mass is dominant
- At high speed:
  - Aerodynamic drag is dominant
- The exact crossover varies vehicle to vehicle.

City driving < 40mph

Everything else > 40mph

An Example: Automotive



F_T
- Uprating the engine/motor
- Increasing the battery capacity

F_H
- Reduce electric draw

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

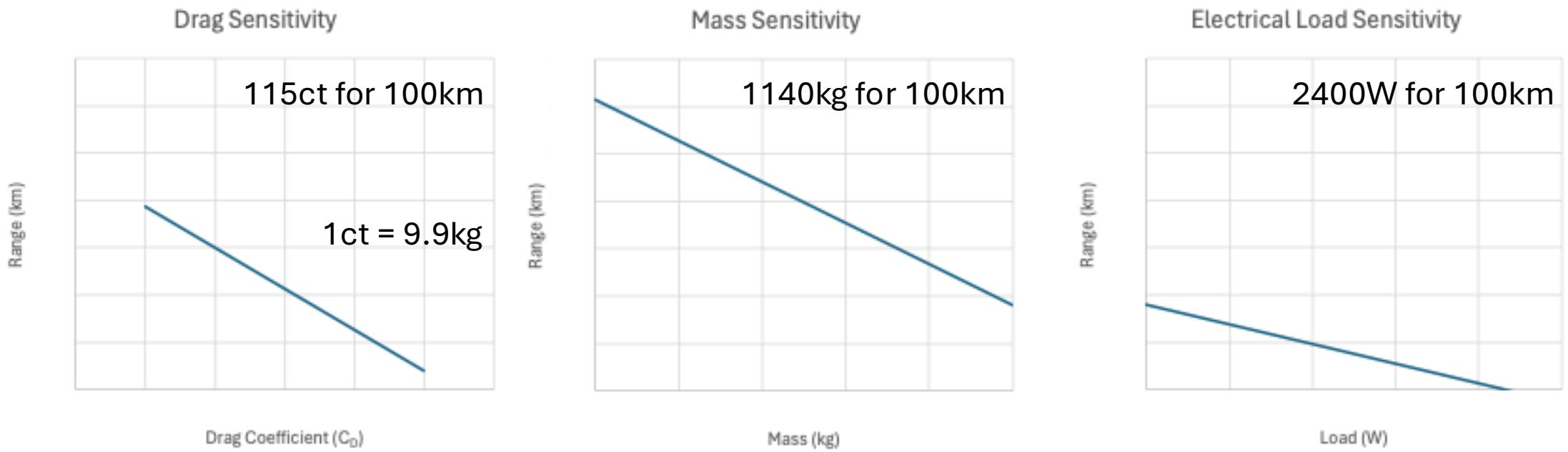
$$F_\mu = \mu\, mg$$

Reduce friction coefficient

Reduce mass

An Example: Automotive

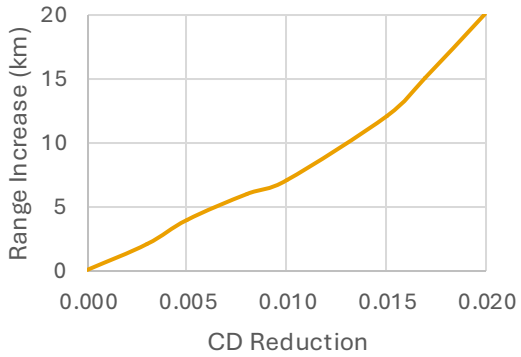
Achieving an additional 100km of range requires a reduction of **115 drag counts**, a decrease of **1140 kilograms** in vehicle mass, or a cut of **2400 watts** in power consumption.



*these numbers are for illustrative purposes and are not based upon a particular vehicle

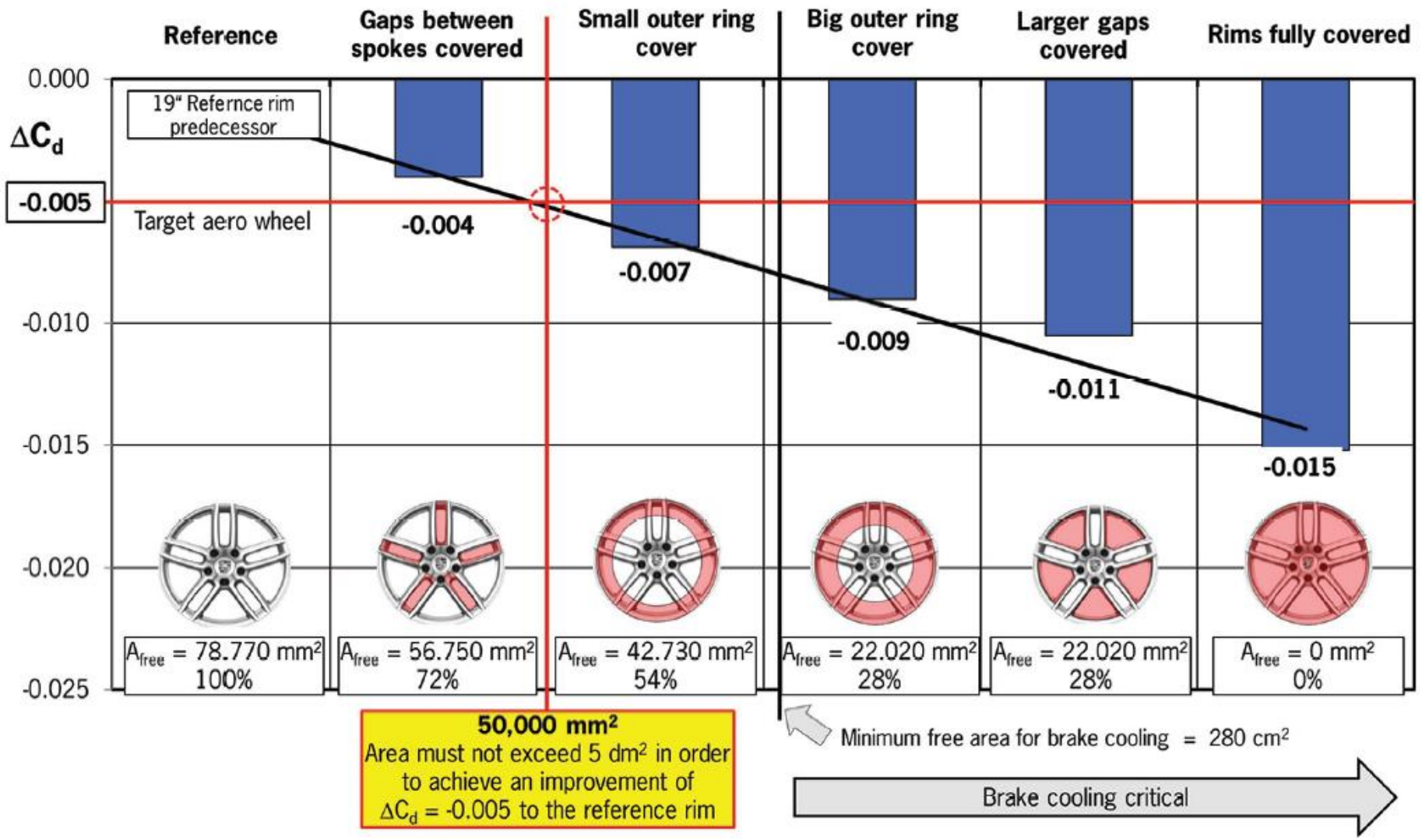
An Example: Automotive

- Result: +15 to 20 km extra range (on 77 kWh battery)
- Efficiency improvement: ~3-5% at highway speeds.



- Aero Optimisation through:
  - Aero wheels
  - Active grille shutters
  - Lower ride height
  - Smoother underbody panels
  - Mirrors and rear spoiler

An Example: Automotive



An Example: Automotive

Other areas for consideration in aerodynamic optimisation:

Front End
- Bonnet angle
- Transition radius to bonnet
- Chin radius
- Front corner radius

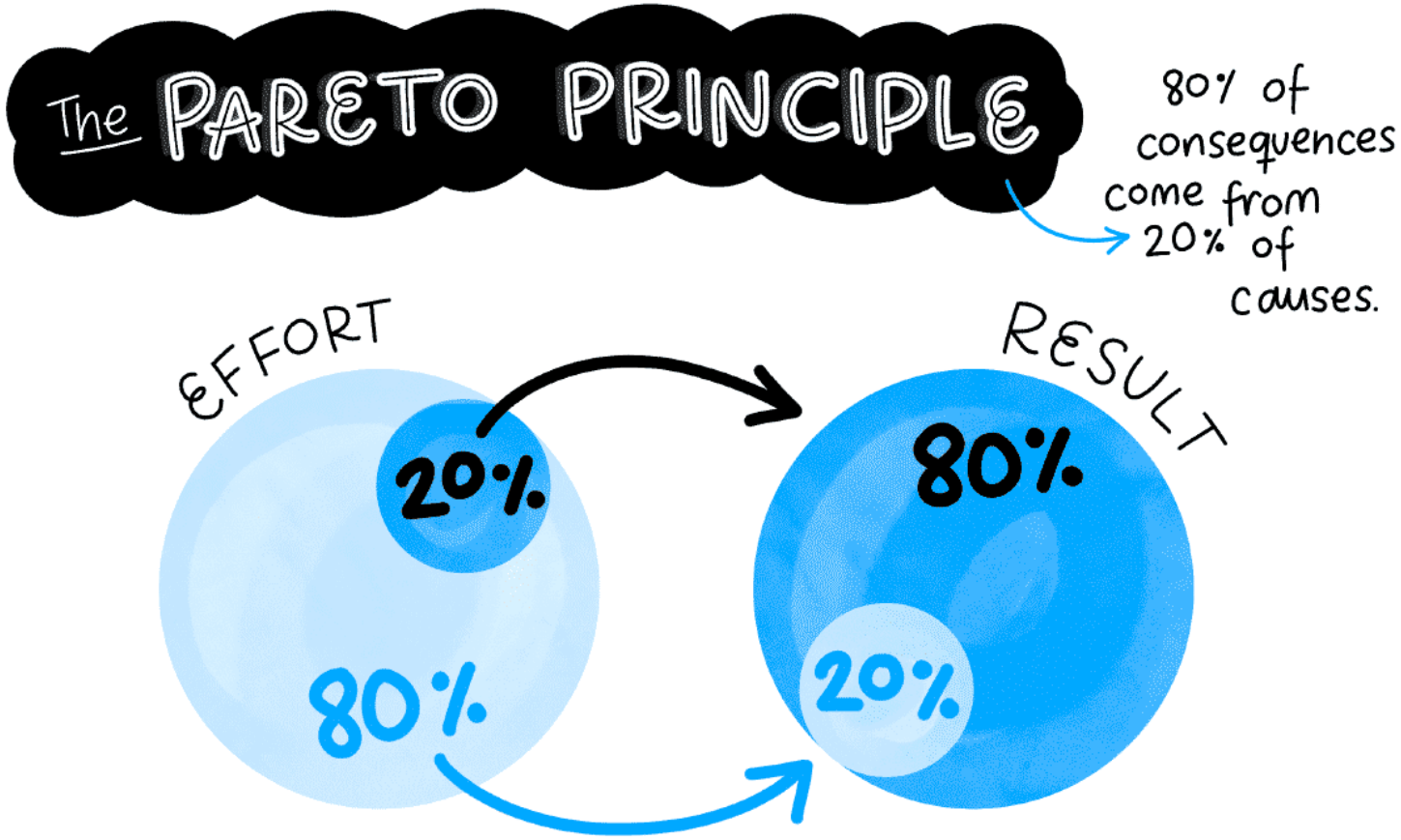
Greenhouse and Body Side
- Windscreen inclination
- A-piller
- Roof
- Body side curvature

Rear End
- Rear screen angle
- Boot length
- Boat tail

Additional Considerations Engineering
- Reduce cooling leakage
- Flat floor

Additional Considerations Aerodynamics
- Active aero:
- Low drag cooling system

The Law of Diminishing Returns



A Big Thank You