# Energy and Transportation

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Varenna, July 2014

# Prelude: conversion efficiencies

- Mechanical ↔ Electrical energy

| | |
|---|---|
| Dynamo, generator | 80 – 98 % |
| Electric motor | 80 – 98 % |

- HEAT → Mechanical energy ($\eta < 1 - T_1 / T_2$)

| | |
|---|---|
| Steam turbine | 40 – 58 % |
| Fuel *to* electricity at home | 33 – 40 % |
| Petrol engine | 20 – 25 % |
| Diesel engine | 25 – 30 % |

- Food → Mechanical energy 20 – 25 %

# *Transportation* Key: RESISTANCE

- Resistance = force = work / distance
- 1 newton = 1 J/m = 1 kJ/km

# Two types of resistance

- Rolling resistance $\boldsymbol{F}_{\mathrm{r}}$

  Rubber tires: $\int \boldsymbol{F}.\mathrm{d}\boldsymbol{s} \neq 0$

  $\boldsymbol{F}_{\mathrm{r}}$ is proportional to weight

  → $\boldsymbol{F}_{\mathrm{r}} = C_{\mathrm{r}} \times mg$

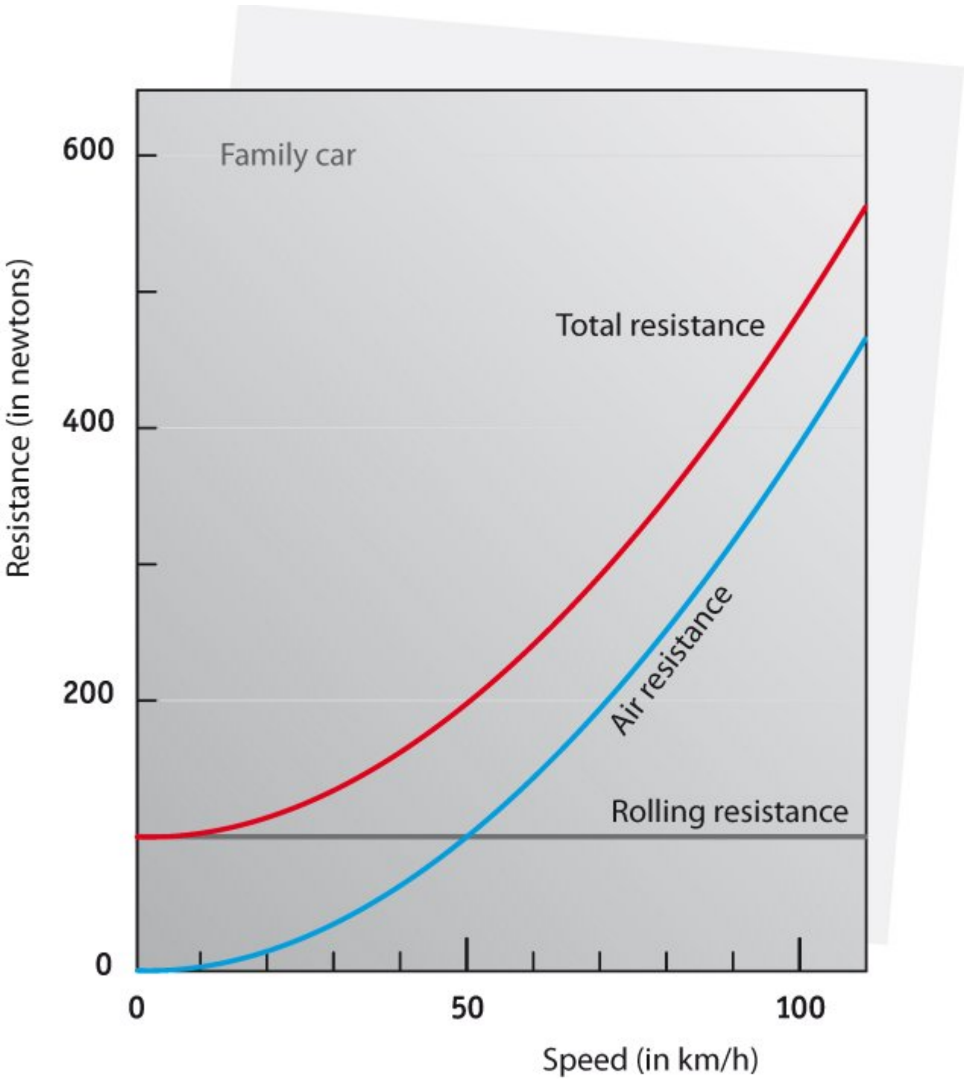
- Air resistance ('Drag') $\boldsymbol{F}_{\mathrm{d}}$

  $\boldsymbol{F}_{\mathrm{d}} = C_{\mathrm{d}} \times A \times \tfrac{1}{2} \rho v^2$ (cf. Bernoulli)

# Resistances for a car

**Model car**:

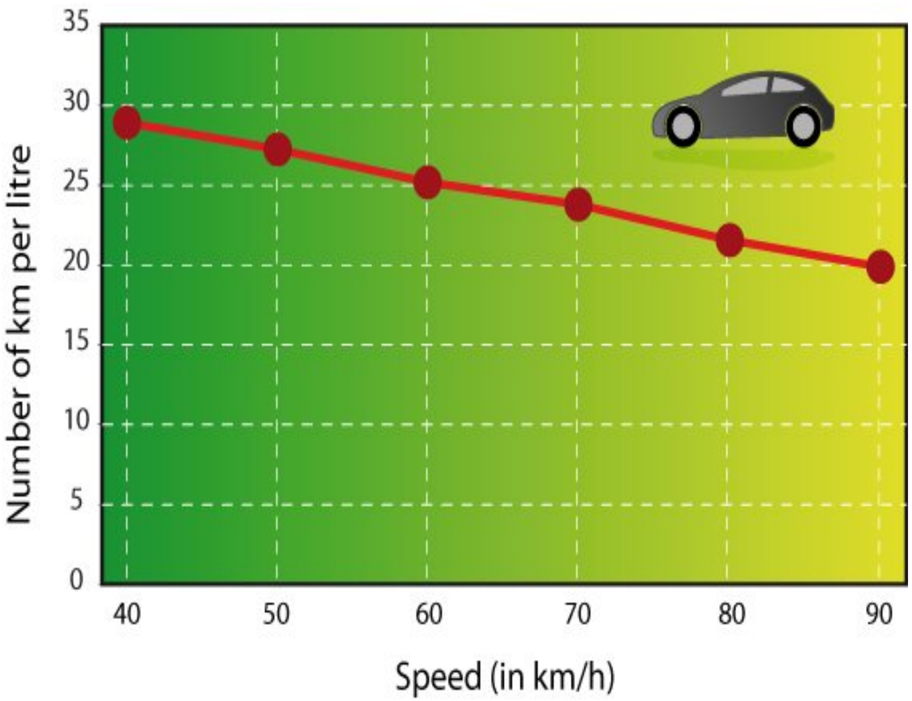
- $m = 1000$ kg
- $C_r = 0.01$
- $C_d = 0.4$
- $A = 2\ m^2$



# Car in practice (not ***that*** bad at high speed):

- Engine efficiency >
  if speed >

- Experiment:
  (Toyota Yaris, 5th gear)



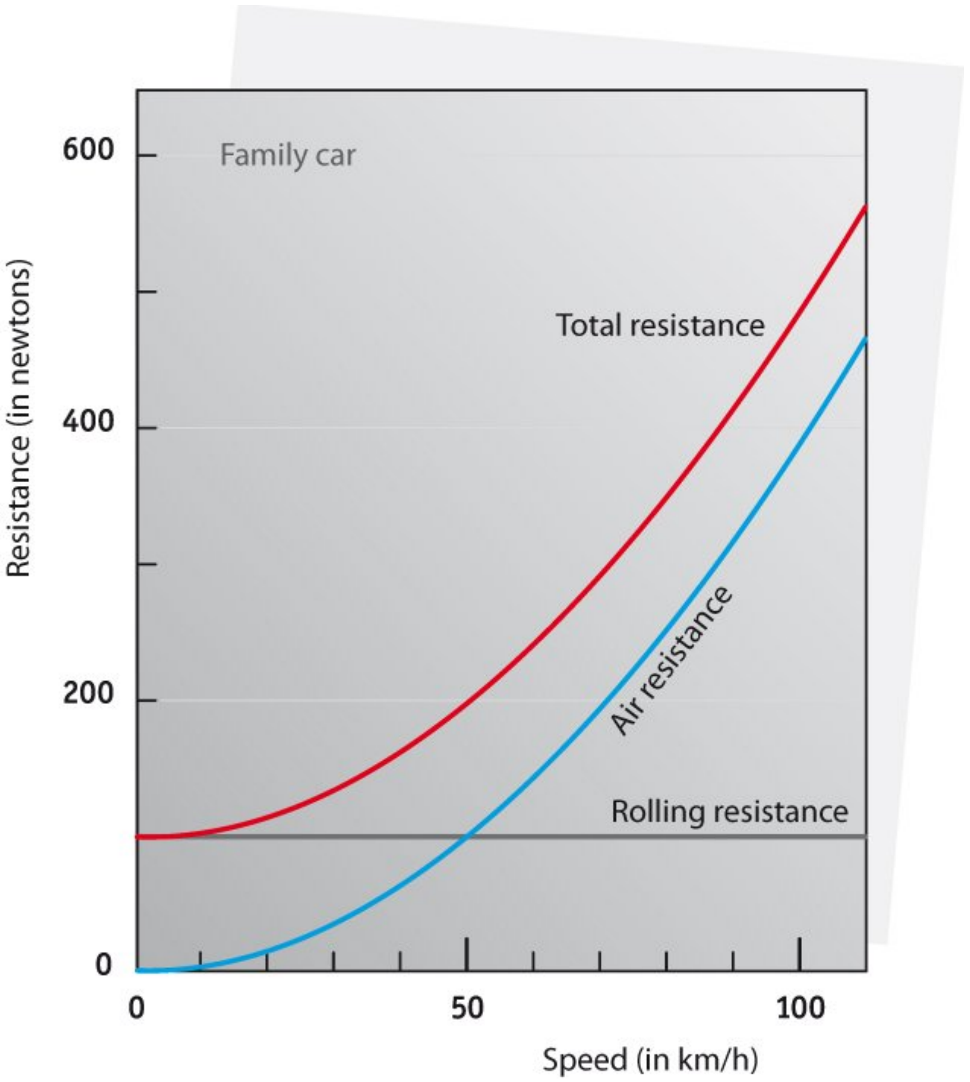
# Power (horizontal road, constant speed)

$P = F \times v$

$v = 100$ km/h $\approx 30$ m/s

→ $F \approx 500$ N *(see graph)*

→ $P \approx 15$ kW



# Stopping/accelerating *vs*. driving

- *Stop and accelerate*: $E = \frac{1}{2} mv^2$

  Take m =1300 kg and v = 100 km/h = 28 m/s

  → $\frac{1}{2} mv^2 = 510$ kJ

- *Driving distance for 510 kJ?*

  Resistance at 100 km/h ≈ 500 N

  → Drive 510 kJ / 500 N ≈ 1 km

  *So for the energy of one stop (100 km/h ↔ 0)*

  *we can drive 1 km*

# Room for improvement

**Model car**

- m = 1000 kg
- $C_D$ = 0.40
- A = 2 $m^2$
- Engine efficiency = 0.2
- Consumption **7** L/100 km

**High efficiency car (XL1)**

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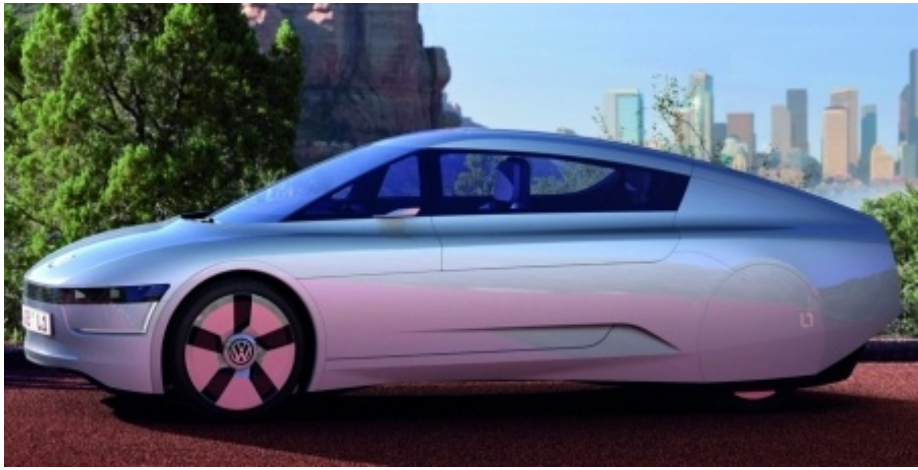

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- Consumption **2** L/100 km
- Diesel engine 800 cc, 35 kW
- Electr. Motor (50 km), 20 kW
- Hybrid: cons. **1** L/100 km
- Top speed 160 km/h

# (semi-) Electric cars

- Hybrid (uses <u>fuel</u> more efficiently)
- Plug-in hybrid (drives partially on electricity)
- All-electric car (range as yet limited: batteries)

# Your car Electric?

- Power for driving ≈ 15 kW
- Energy for driving 7 hours ≈ 100 kWh *(cheap!)*

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*Charging?*

- Charge from standard outlet: 3,5 kW
- Charging time ≈ 4 × driving time *(long!)*

# Storing electricity

*Batteries and capacitors*

| | | |
|---|---|---|
| Lead battery: 40 Ah×12 V ≈ 0,5 kWh | | ≈0,03 kWh/kg |
| NiMH battery | | ≈0,06 ,, |
| Li-ion battery | | ≈0,15 ,, |
| Li-ion polymer battery | (LiPo) | ≈0,20 ,, |
| Supercapacitor | | ≈0,005 ,, |
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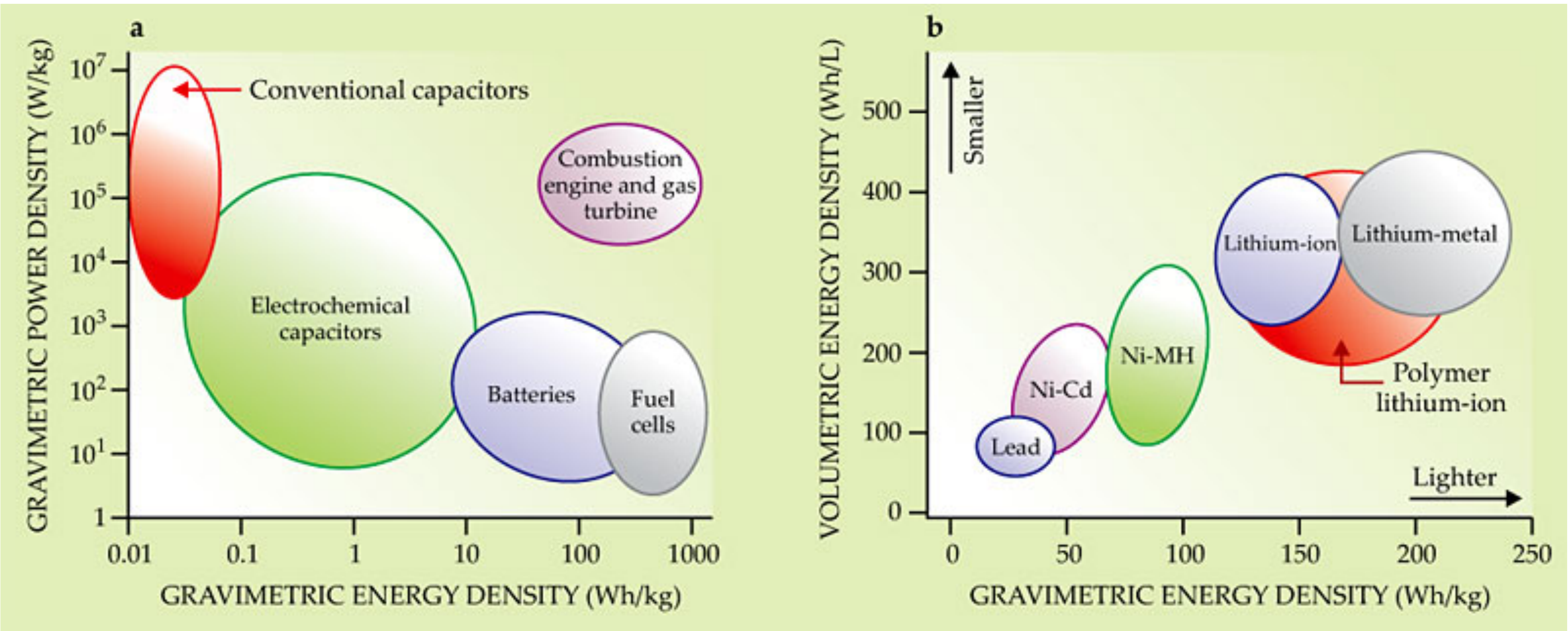
Remember: 1 hour driving ≈15 kWh

# Capacitors and Batteries

(from: Physics Today, December 2008)

- *Capacitors* for Power…..............*Batteries* for Energy



# All-electric car: Example (BMW i3)

| | |
|---|---|
| • Mass | 1195 kg |
| • Electromotor max power | 125 kW |
| • Battery (Li-ion) | 19 kWh |
| • Energy use per 100 km | 14-17 kWh |
| • Max. range | 130-160 km |
| • Charge to 80% - Rapid, DC: | 0.5 h |
| - AC outlet: | 6-8 h |

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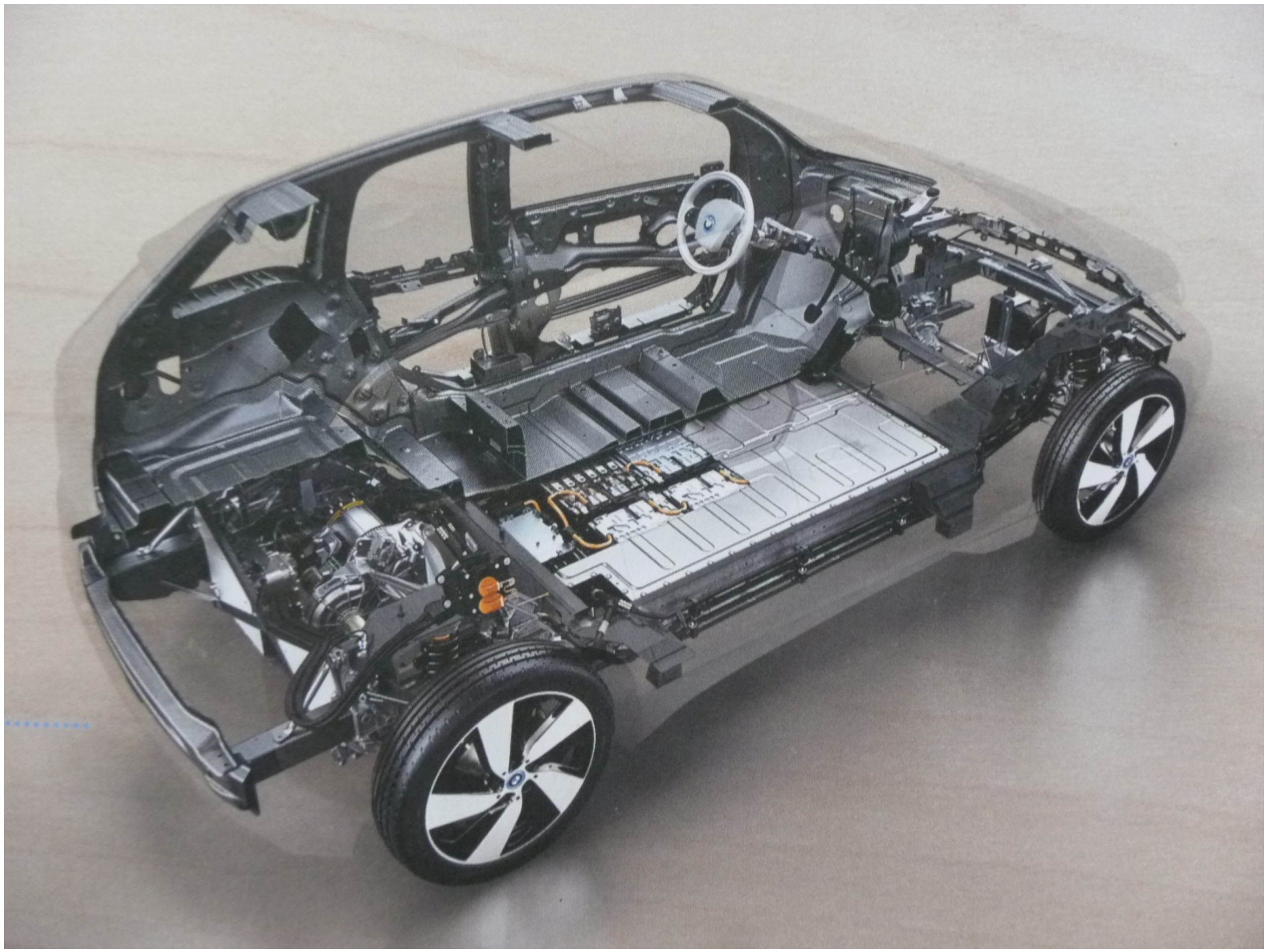
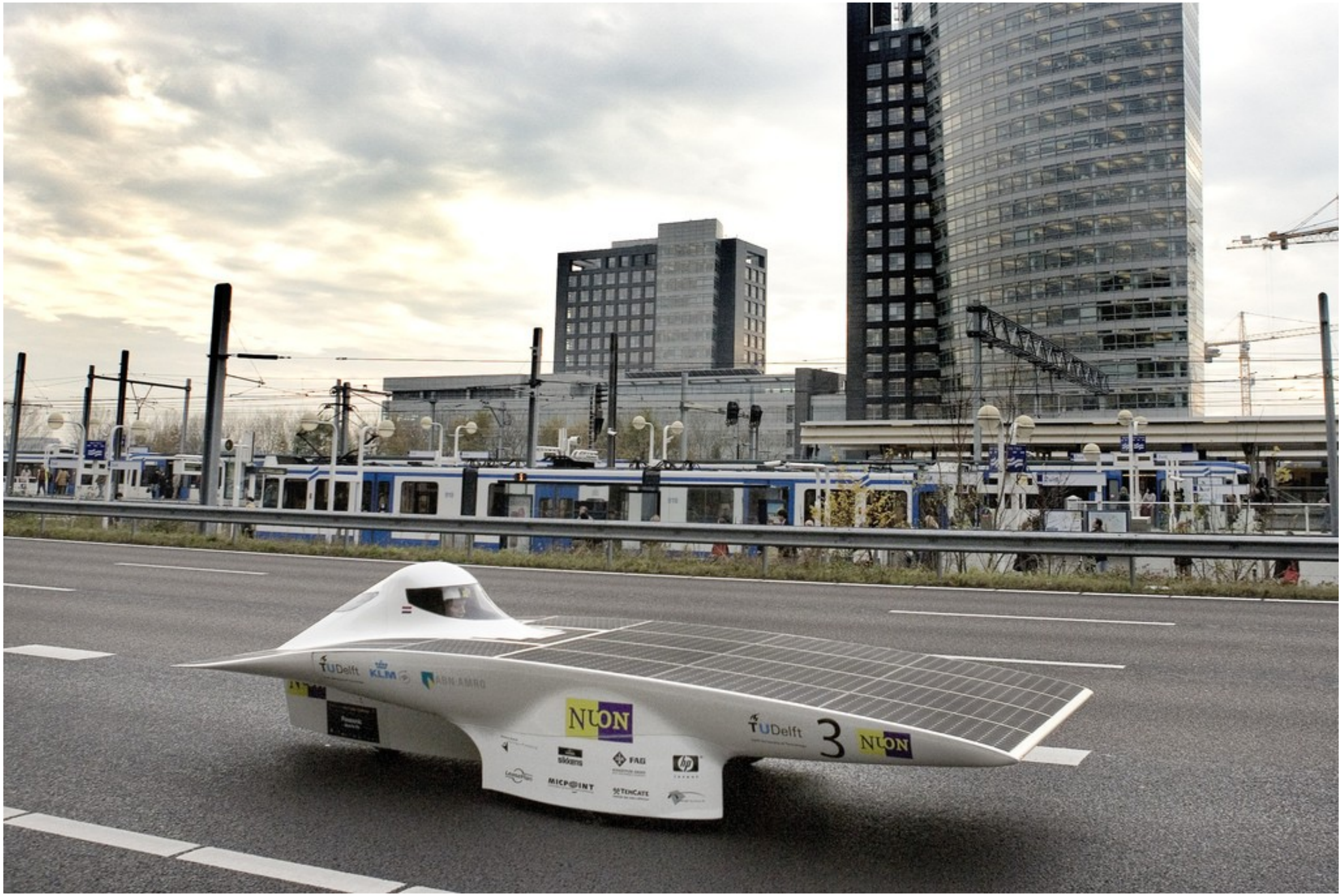


# All-electric car: Example (BMW i3)

# What about Solar Car ??



# What about Solar Car ??

- Remember: Solar irradiance max. = 1 kW/$m^2$
- Assume efficiency solar cells 50%
- For 15 kW: needed 30 $m^2$
- So solar family care without storage:

  beyond hope!

# ….and Hydrogen?

Not ideal for mobile storage: Boiling point 20.4 K

*1. Liquid*?? Heat of vaporisation small → boil-off

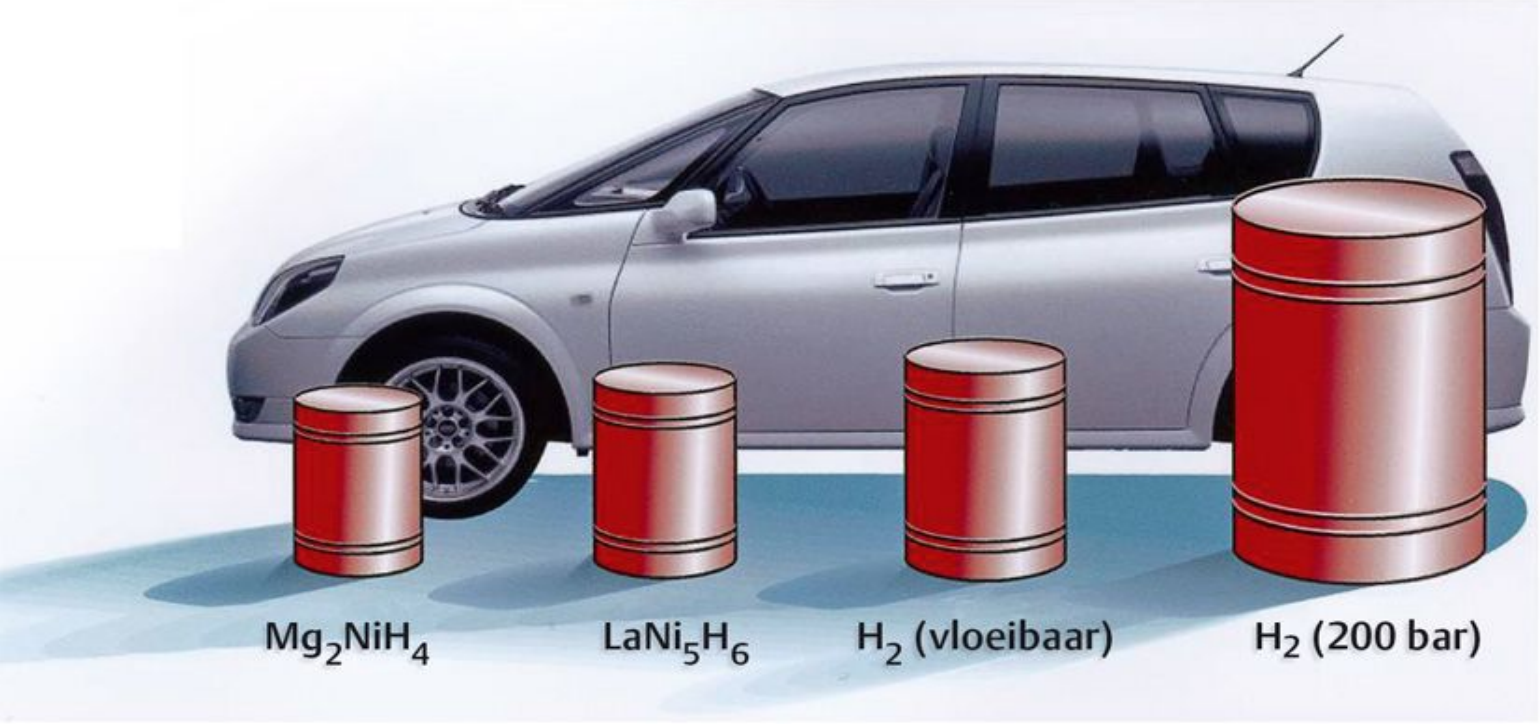
*2. Gas*? compress→ bulky / heavy (*Not* ideal gas!)

*3. Metal hydrides*? heavy

# Hydrogen properties

| | | |
|---|---|---|
| • Heat of combustion | (higher) | 142 MJ/kg |
| | (lower) | 120 MJ/kg |
| • Density (at 0 $^{o}$C, 1 bar) | | 0.090 kg/m$^3$ |
| • Boiling point | | 20.4 K |
| • Density of liquid $H_2$ | | 71.0 kg/m$^3$ |

# Hydrogen car....so far



# Future electric car: batteries or $H_2$?

Probably batteries:

- Infrastructure ≈ present
- Change-over can be gradual

# Intelligent Transport Systems

*Objectives:*

- Increase Road Capacity
- Reduce Energy use (Drag!)
- Improve traffic safety

# Cooperative Adaptive Cruise Control

(J. Ploeg et al; TU/e)

- Automatic short-distance vehicle following
- Use: wireless communication & on-board sensors
- One- or two vehicle look-ahead communication

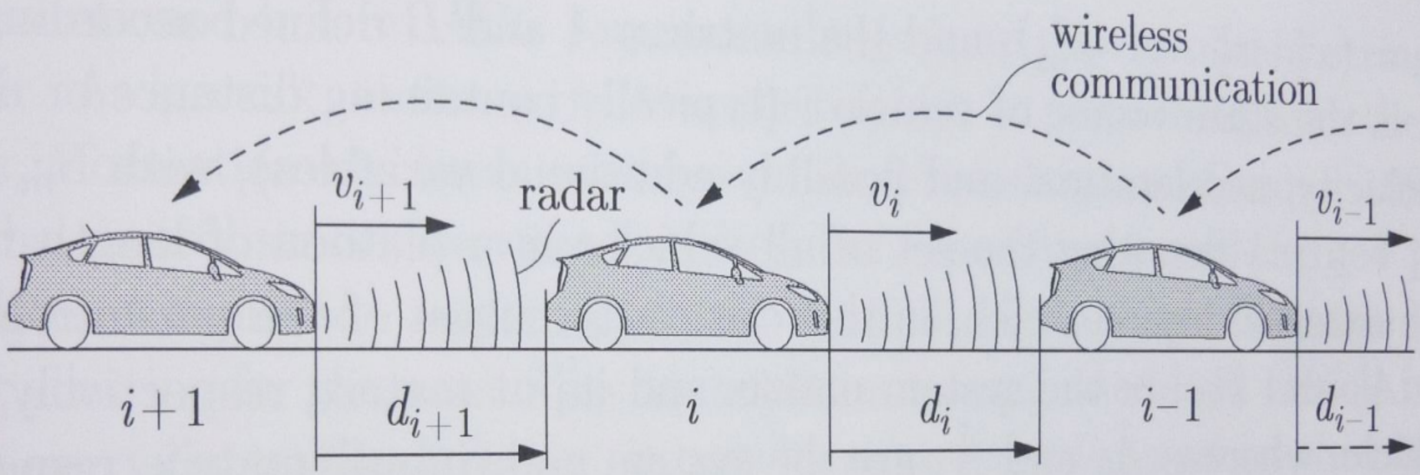



**Figure 4.1:** A homogeneous platoon of vehicles equipped with CACC.

# **C**ooperative **A**daptive **C**ruise **C**ontrol

(J. Ploeg et al; TU/e)

*Requirements*

- Accurately follow preceding vehicle
- String stability
- Graceful degradation if communication errors

# Cooperative Adaptive Cruise Control Prototype platoon

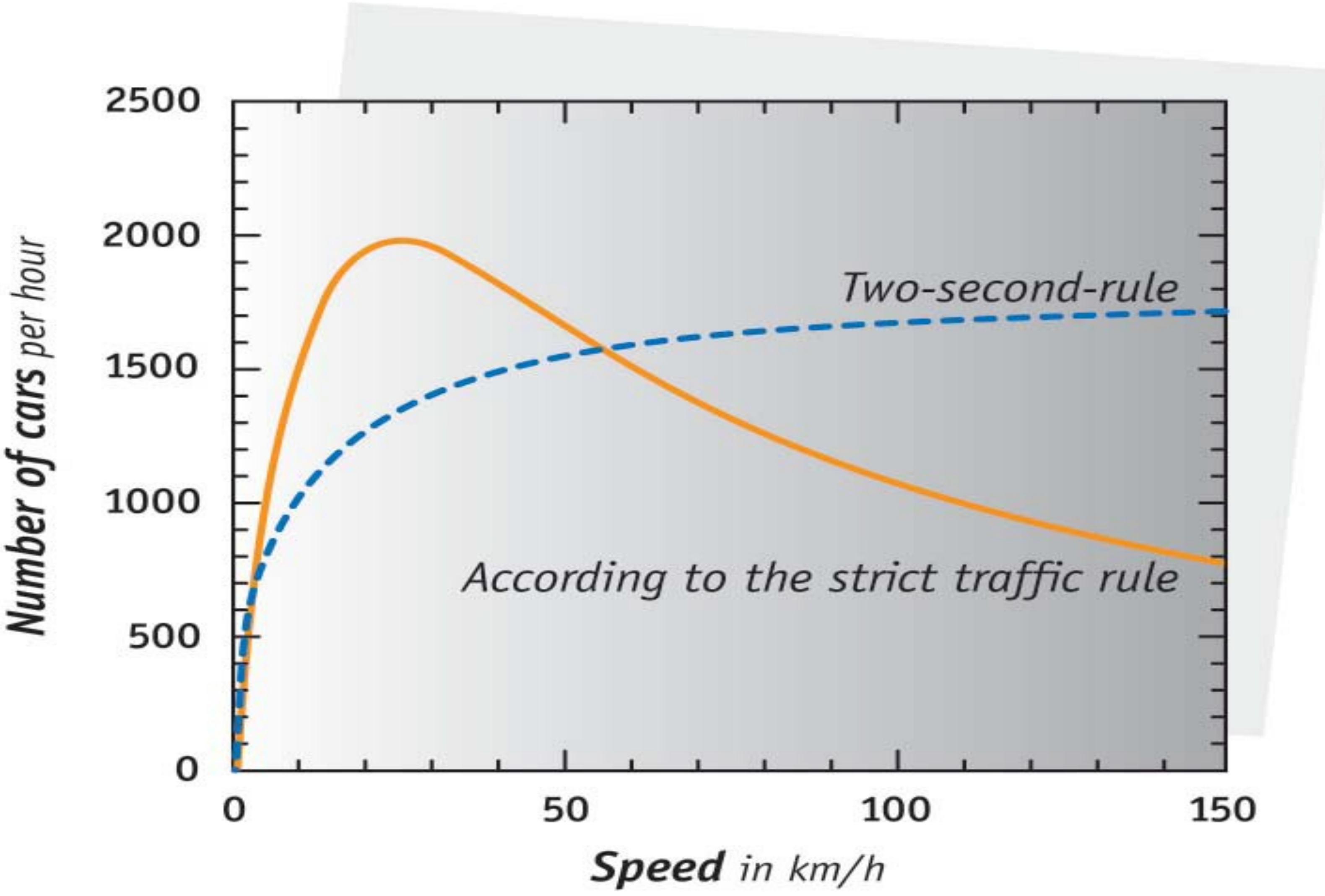
# Road Capacity and Safety

- Capacity (throughput) $C = nv$
- Safe spacing (e.g., official Dutch traffic rule):

$$n = (L + \tau v + v^2/2a)^{-1}$$

$$C = v/(L + \tau v + v^2/2a)$$

# Road Capacity and Safety



# Buses

- $C_r$ and m <u>per seat</u> similar to car
  → Rolling resistance <u>per seat</u>: bus ≈ car
  So at low speed no advantage

- Drag <u>per seat</u>: bus has *smaller* A (factor 3 - 4)
  bus has *larger* $C_d$ (factor 1.5 - 2)
  Net effect: bus has smaller drag (factor 2-3)
  So at high speed bus beats car by factor 2 - 3

# Trains

- *Rolling resistance*: $C_r$ much smaller (steel wheels!)

  m per seat somewhat larger

  Net effect rolling resistance: train wins by factor 3

- *Drag* per seat: train has *smaller* A (factor 20)

  train has *larger* $C_d$ (factor 2)

  Net effect: train has smaller drag by factor 10

  So train beats car by factor 3 - 10

# Trains: drawbacks

- Large m disadvantage if stops are frequent:
  Energy of 1 stop ≈ 10 km ride
  →*Frequent stops can kill advantage unless regenerative breaking*

- Electric heating NOT free (*cf*. car, bus)

# Aircraft

- Only drag
- HIGH SPEED → high drag......... *But*:
- Air density (10 km) ≈ ¼ density at sea level
- Streamline excellent (low $C_d$)

Result: 30 – 35 pass.km/L (full plane)

cf. car: 60 pass.km/L (full car)

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- Calculation Hindenburg (v = 135 km/h = 37.5 m/s)
- Power 3560 kW, = F × v
- F = 3560 kW / 37.5 m/s = 95 kN (100 passengers)
- F per passenger = 950 N (cf. car: 100-150)
- So: beyond hope

# Bicycles

- Human engine ≈ 100 W

= Climbing stairs, 1 step/s

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- $P = mg\,\mathrm{d}h/\mathrm{d}t$

  $P = 70 \times 10 \times 0.15$ W

  ≈ 100 W (mechanical)

# Bicycles

- Energy use bicycle? Depends on speed, ….
- Estimate:

100 W mechanical = 400 W food (remember $\eta \approx 1/4$ )

400 W during 1 day = 1 litre of oil

Cycling during 1 day = 24 h: 500 km

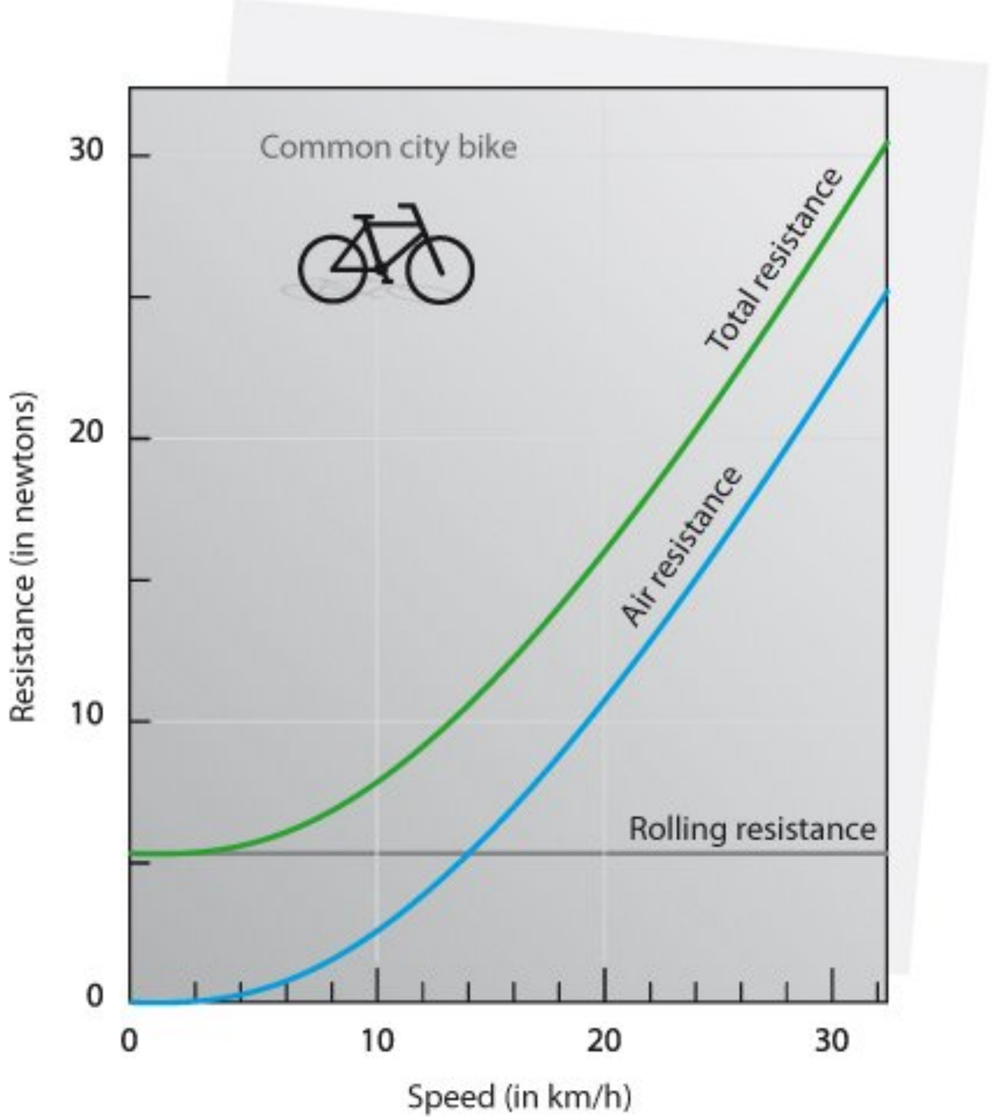
*A bicycle runs 1 L per 500 km (BUT….)*

# Resistances for a city bike

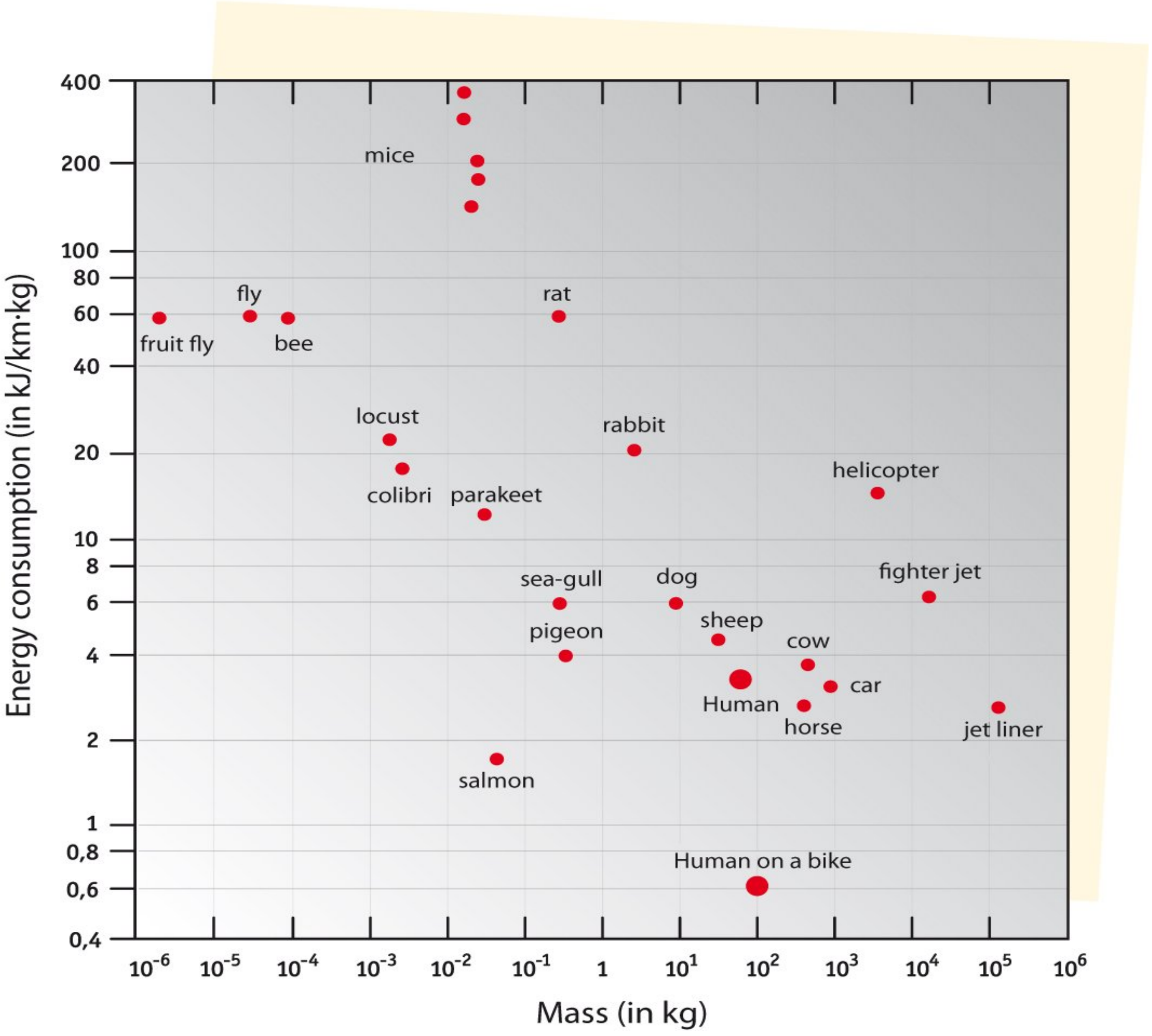
Standard city bicycle:

- $m = 90$ kg
- $C_r = 0.006$

- $C_d = 1.0$
- $A = 0.6\ m^2$



# The bicycle beats them all….



# …and can even be improved: HPV

- Reduce drag for speed records:

  133.3 km/h

Sam Wittingham

(2009, Battle Mountain, Nevada)

# Energy efficiency: comparison

| | Number of passengers | Speed (km/h) | Energy efficiency (pass.km /litre) |
|---|---|---|---|
| Bicycle | 1 | 20 | 500 |
| Electric bicycle | 1 | 20 | 400 |
| Train | 250 | 130 | 250 |
| Bus | 50 | 100 | 170 |
| Car | 4 | 100 | 60 |
| TGV | 377 | 300 | 50 |
| Aircraft | 400 | 900 | 30* |
| Passenger ship | 2000 | 50 | 4 |

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- Environmental concerns? *Cycle….and recycle!*