Efficient transportation and energy storage
Prelude: rules of thumb

• 1 L of oil, gasoline
  \[ \approx 40 \text{ MJ} \]
  \[ \approx 10 \text{ kWh}_{th} \]
  \[ \approx 10 \text{ MJ} \]
  \[ \approx \frac{1}{4} \text{ L of oil} \]

• Daily food
  \[ \approx 10 \text{ MJ} \]
  \[ \approx \frac{1}{4} \text{ L of oil} \]

• 100 W continuous
  \[ = 100 \times 24 \times 3600 \text{ J/day} \approx 10 \text{ MJ/day} \]
  \[ \approx \frac{1}{4} \text{ L of oil/day} \]
Prelude (2): conversion efficiencies

• Mechanical ↔ Electrical energy
  Dynamo, generator 80 – 98 %
  Electric motor 80 – 98 %

• HEAT → Mechanical energy ($\eta < 1 - \frac{T_1}{T_2}$)
  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 efficiency

*key*: RESISTANCE

- Resistance = force = work / distance
- 1 newton = 1 J/m = 1 kJ/km
Two types of resistance

• Rolling resistance $F_r$
  
  *e.g.* Rubber tires: $\int F \, ds \neq 0$
  
  $\rightarrow F_r = C_r \times mg$

• Air resistance (‘Drag’) $F_d$
  
  $F_d = C_d \times A \times \frac{1}{2} \rho v^2$ (cf. Bernoulli!)
Resistances for a car

Model car:
- \( m = 1000 \text{ kg} \)
- \( C_r = 0.01 \)
- \( C_d = 0.4 \)
- \( A = 2 \text{ m}^2 \)
Power (horizontal road, constant speed)

\[ P = F \times \nu \]
\[ \nu = 100 \text{ km/h} \approx 30 \text{ m/s} \]
\[ F \approx 500 \text{ N} \]
\[ \rightarrow P \approx 15 \text{ kW} \]
Car in practice *(not* *that* *bad* *at* *high* *speed)*:

- Engine efficiency > if speed >
- Experiment: *(Toyota Yaris, 5th gear)*
Stopping/accelerating vs. driving

• **Stop and accelerate**: \( E = \frac{1}{2} m v^2 \)
  
  Take \( m = 1300 \text{ kg} \) and \( v = 100 \text{ km/h} = 28 \text{ m/s} \)
  
  \( \frac{1}{2} m v^2 = 510 \text{ kJ} \)

• **Drive distance for 510 kJ?**
  
  Resistance at 100 km/h \( \approx 500 \text{ N} \)
  
  \( \rightarrow \) Drive \( \frac{510 \text{ kJ}}{500 \text{ N}} \approx 1 \text{ km} \)

*So for the energy of one stop (100 km/h \( \leftrightarrow 0 \)) we can drive 1 km*
(semi-) Electric cars

• Hybrid (uses fuel more efficiently)
• Plug-in hybrid (drives partially on electricity)
• All-electric car (range as yet limited: batteries)
• Hydrogen + fuel cells
Buses

• $C_r$ and $m$ per seat similar to car
  $\rightarrow$ Rolling resistance per seat: bus $\approx$ car
  So at low speed no advantage

• Drag per seat: 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!) 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 $\approx 10$ km ride
  $\rightarrow$ *Frequent stops can kill advantage*
  *unless regenerative breaking*

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

- Only drag
- HIGH SPEED → high drag \( \cdots \cdots \) \textit{But}:
- Air density (10 km) \( \approx \) \( \frac{1}{4} \) 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)
The Zeppelin

• No rolling resistance. BUT:
  Frontal area per passenger!! (13 m² Hindenburg)
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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 $\approx 100 \text{ W}$
- Climbing stairs, 1 step/s
Bicycles

• Human engine \(\approx 100 \text{ W}\)

  = Climbing stairs, 1 step/s

• \(P = mg \frac{dh}{dt}\)

  \(P = 70 \times 10 \times 0.15 \text{ W}\)

  \(\approx 100 \text{ W (mechanical)}\)
Bicycles

- Human engine $\approx 100 \text{ W}$
  - Climbing stairs, 1 step/s

- This is long-duration
  (Peak power $\approx 1 \text{ kW}$)

- $P = mg \frac{dh}{dt}$
  - $P = 70 \times 10 \times 0.15 \text{ W}$
    $\approx 100 \text{ W (mechanical)}$
Bicycles

- Energy use bicycle? Depends on speed, ....
- Estimate:
  
  100 W mechanical = 400 W food  \(\text{remember } \eta \approx \frac{1}{4}\)  
  
  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:

- $m = 90 \text{ kg}$
- $C_r = 0.006$
- $C_d = 1.0$
- $A = 0.6 \text{ m}^2$
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

<table>
<thead>
<tr>
<th>Mode</th>
<th>Number of passengers</th>
<th>Speed (km/h)</th>
<th>Energy efficiency (pass.km/litre)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bicycle</td>
<td>1</td>
<td>20</td>
<td>500</td>
</tr>
<tr>
<td>Electric bicycle</td>
<td>1</td>
<td>20</td>
<td>400</td>
</tr>
<tr>
<td>Train</td>
<td>250</td>
<td>130</td>
<td>250</td>
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<tr>
<td>Bus</td>
<td>50</td>
<td>100</td>
<td>170</td>
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<tr>
<td>Car</td>
<td>4</td>
<td>100</td>
<td>60</td>
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<td>TGV</td>
<td>377</td>
<td>300</td>
<td>50</td>
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<tr>
<td>Aircraft</td>
<td>400</td>
<td>900</td>
<td>30</td>
</tr>
<tr>
<td>Passenger ship</td>
<td>2000</td>
<td>50</td>
<td>4</td>
</tr>
</tbody>
</table>
Future energy carriers

*Mobile storage systems*

- Advanced batteries
- Supercapacitors
- Hydrogen
- Flywheels
- ....
Storing electricity

**Batteries and capacitors**

Lead battery: \(40 \text{ Ah} \times 12 \text{ V} \approx 0.5 \text{ kWh} \rightarrow \approx 0.03 \text{ kWh/kg} \)

NiMH battery \(\approx 0.06\) „

Li-ion battery \(\approx 0.15\) „

Li-ion polymer battery (LiPo) \(\approx 0.20\) „

Supercapacitor \(\approx 0.005\) „

*expected:* \(\approx 0.02\) „
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Remember: 1 hour driving $\approx 15$ kWh
Capacitors and Batteries
(from: Physics Today, December 2008)

- Capacitors for Power................. Batteries for Energy
YOUR car electric?

- Power for driving ≈ 15 kW
- Energy for driving 7 hours ≈ 100 kWh (cheap!)
YOUR car electric?

- Power for driving $\approx 15$ kW
- Energy for driving 7 hours $\approx 100$ kWh (cheap!)

Charging?
- Charge from standard outlet: 3,5 kW
- Charging time $\approx 4 \times$ driving time (!)
Solar family car (15 kW) 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 °C, 1 bar) 0.090 kg/m³

• Boiling point 20.4 K

• Density of liquid H₂ 71.0 kg/m³
Hydrogen car....so far
Future electric car: batteries or $\text{H}_2$?

Probably batteries because:

• Infrastructure $\approx$ present
• Change-over can be gradual
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BUT switch to electric may be slow....
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• Environmental concerns? *Cycle….and recycle!*
• Improvements batteries & capacitors vital
• **Nothing** beats the comfort of fossil fuels
  So…..
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• Bus beats car by factor 2 - 3
• Train beats car by factor 3 - 10
• Plane loses from car by factor 2
• Environmental concerns? *Cycle....and recycle!*
• Improvements batteries & capacitors vital
• **Nothing** beats the comfort of fossil fuels

So.....we better make them last long!