Energy Generation, Storage, and Transformation

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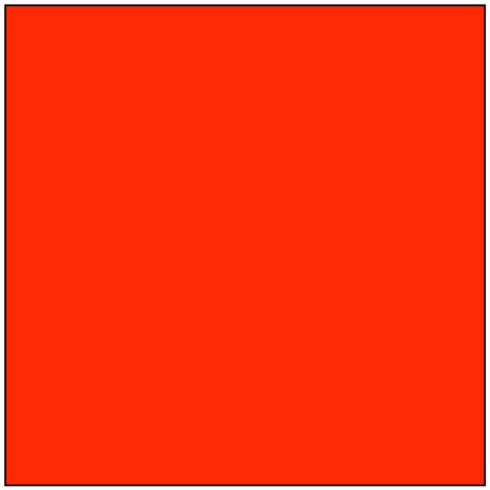
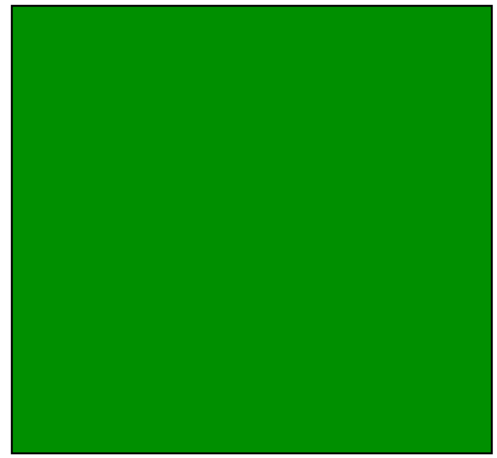
3. The Balance Sheet

Consumption		Production (sustainable)
	vs	
Transport		Wind
Heating/cooling		Solar(PV,thermal,biomass)
Lighting		Hydroelectric/wave/tide
Food		Geothermal
Manufacturing		Nuclear?

Units

Energy: SI unit = joule   (1 J = 1 kg m^2 s^{-2})

Power: = Energy/time

SI unit = watt   (1 W = 1 J s^{-1} = 1 kg m^2 s^{-3})

Prefixes

10^3	10^6	10^9	10^{12}	10^{15}
kilo	mega	giga	tera	peta
(k)	(M)	(G)	(T)	(P)

e.g. 3.2 x 10^{17} W = ?

Units

Alternative units used in this book:

Energy: kWh (kilowatt-hour)

("one unit" on electricity bills)

power x time = energy

e.g. Toaster with power 1 kW consumes 1 kWh/h.

1 kW x (1000 W/1 kW) x (1 Js^{-1}/1 W) x 1h x (3600 s/1 h) = 3.6 MJ

Power: = kWh/d

1 kWh/d x (3.6x10^6 J/1 kW) x (24 h x 3600 s/1 d) = 42 W

In general, these values are normalized "per person"

e.g. 80 kWh/d/p = 80 kWh per day per person

cf.Dr. J. Kassebaum's suggestion of normalization to GDP. (Mackay deliberately chooses not to introduce economics, and to consider only energy.)

Pros and cons?

Energy and Thermodynamics

The first and second laws are the bones and the flesh of thermodynamics; by comparison, the zeroth and third laws are mere hat and slippers."

Daniel Sheehan

1. Energy can neither be created nor destroyed $\Delta U = q + w$

2. Entropy increases $dS \geq 0$ with $\begin{cases} dS = dq / T \\ S = k \ln W \end{cases}$

0. Transitivity of equilibrium $T(A) = T(B)$ and $T(B) = T(C)$ implies $T(A) = T(C)$

3. Absolute zero $S(0K) = 0$

High-grade and low-grade energy

Thanks to the second law, *low-entropy* energy is high-grade energy, and is more valuable than high-entropy energy.

Low entropy	High entropy
“Chemical energy”	“Thermal energy”
“Electrical energy”	

Although energy can always be measured in the same units, it is not always freely interchangeable (and there is no universal “exchange rate”).

e.g. Coal-fired power station:

Chemical energy $\xrightarrow[\text{efficiency}]{40\%}$ Electrical energy

4. Transportation

Cars

We will try to calculate an average energy/power consumption figure in kWh/d/p.

Required data:

1. **Fuel economy** = distance traveled per unit of fuel consumed

(usually measured in mpg)

N.B.

1 UK gallon = 4.54609 L

1 US gallon = 3.78541 L

1 UK gallon = 1.200 US gallon

i.e. Mackay's "average" 33 mpg (UK) converts to 27.5 mpg (US)

New car figures are much better than average figures.

Cars

We will try to calculate an average energy/power consumption figure in kWh/d/p.

Required data:

2. Energy density of gasoline = 46.4 MJ/kg (ORNL Center for Transportation Analysis)

= 34.2 MJ/L

Cars

We will try to calculate an average energy/power consumption figure in kWh/d/p.

Required data:

3. Typical daily distance traveled = 50 km/d/p

Mackay's figures are for UK:

686 bn passenger-km/y ÷ 365.25 d/y = 1.88 bn passenger-km/d

÷ 37.6 M people who drive = 50 km/d/p

Not averaged over all UK citizens

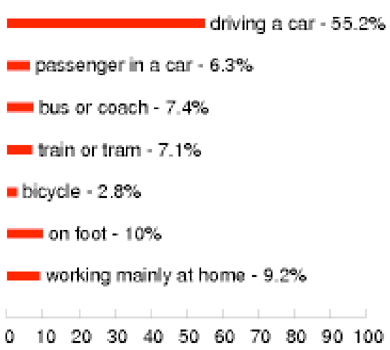
Assumes 1p/car

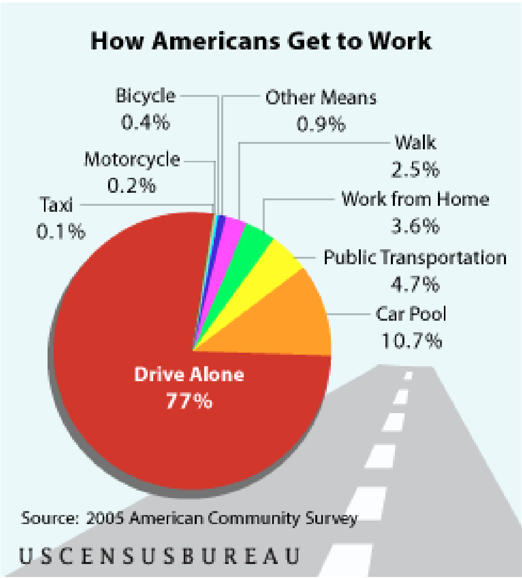
Other options for similar calculations exist

Cars

We will try to calculate an average energy/power consumption figure in kWh/d/p.

Commuting strategies:





Cars

We will try to calculate an average energy/power consumption figure in kWh/d/p.

Using (not particularly carefully selected) US data:

77% of workers (102 M people) drive "solo"

Average commute 16 mi

Assuming *all* commuters drive alone we obtain

100/77 x 102 M commuters = 132 M commuters, and

an average consumption of 26 kWh/d

Neglected: Energy cost of fuel *production* (1.4 units/unit)

Energy cost of vehicle manufacture (etc.)

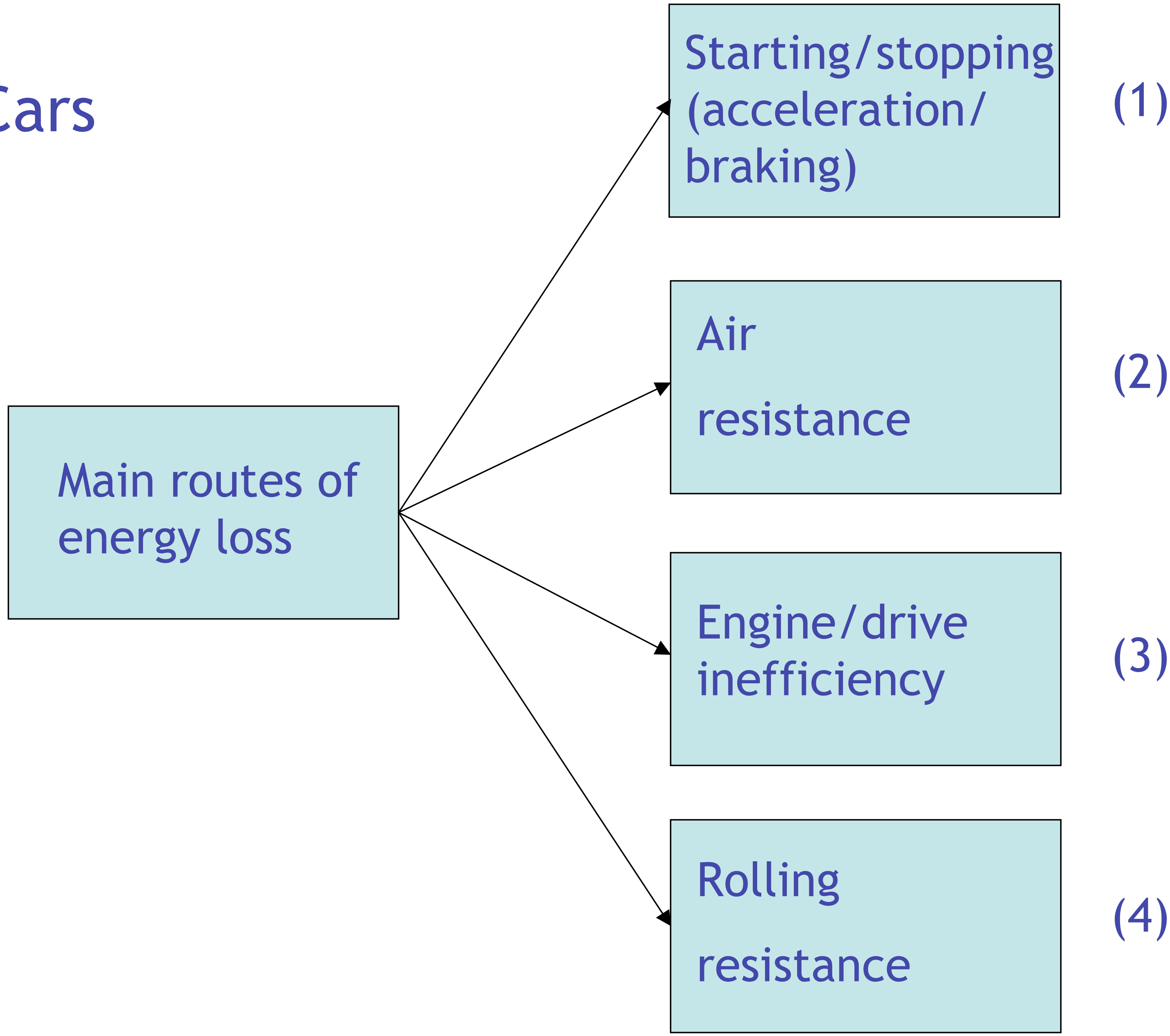
Cars

How efficient are cars?

Where does the energy go?

Can significant improvements be made?

Cars


Main routes of energy loss
Starting/stopping (acceleration/ braking)
(1)
Air resistance
(2)
Engine/drive inefficiency
(3)
Rolling resistance
(4)

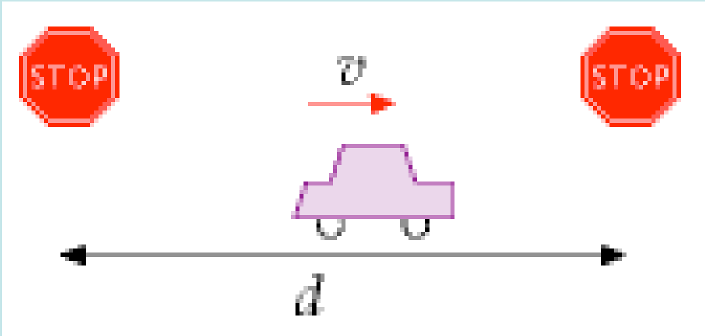
Cars

(1) Acceleration/braking

Requires energy

Discards energy

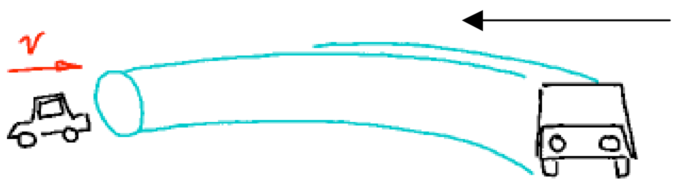
Model stop/start driving as a series of braking events of length d, between which car reaches velocity v.



P_{brakes} = KE/period

i.e. $$P_{brakes} = \frac{1}{2}\frac{m_c v^3}{d}$$

Cars (2) Air resistance



"Tube" of air disrupted by passage of car (made more turbulent).

"Drag area" - slightly smaller than frontal area of (streamlined) car.

$$A = c_d A_{car}$$

KE of displaced air: $$KE_{air} = \frac{1}{2}\rho A v^3 t$$

Power = rate of generation of swirling air = KE/t, i.e.

$$P_{air} = \frac{1}{2}\rho A v^3$$

DRAG COEFFICIENTS	
CARS	
Honda Insight	0.25
Prius	0.26
Renault 25	0.28
Honda Civic (2006)	0.31
VW Polo GTi	0.32
Peugeot 206	0.33
Ford Sierra	0.34
Audi TT	0.35
Honda Civic (2001)	0.36
Citroën 2CV	0.51
Cyclist	0.9
Long-distance coach	0.425
PLANES	
Cessna	0.027
Learjet	0.022
Boeing 747	0.031

DRAG-AREAS (m^2)	
Land Rover Discovery	1.6
Volvo 740	0.81
Typical car	**0.8**
Honda Civic	0.68
VW Polo GTi	0.65
Honda Insight	0.47

Table A.7. Drag coefficients and drag areas.

Cars (2) Air resistance

Only really significant way to reduce drag area is *tandem seating*.

VW prototype

1L/100km = 236 mpg

Cars

Combining braking and air resistance:

$$P = P_{brakes} + P_{air} = \frac{1}{2}\frac{m_c v^3}{d} + \frac{1}{2}\rho A v^3$$

In both cases, power is proportional to velocity *cubed*.

For a given distance, E/d = Pxt/d = P/v, and so energy consumed per unit distance is proportional to v^2.

Halving speed reduces energy consumed by a factor of 4 (if engine efficiency is ignored).

Cars

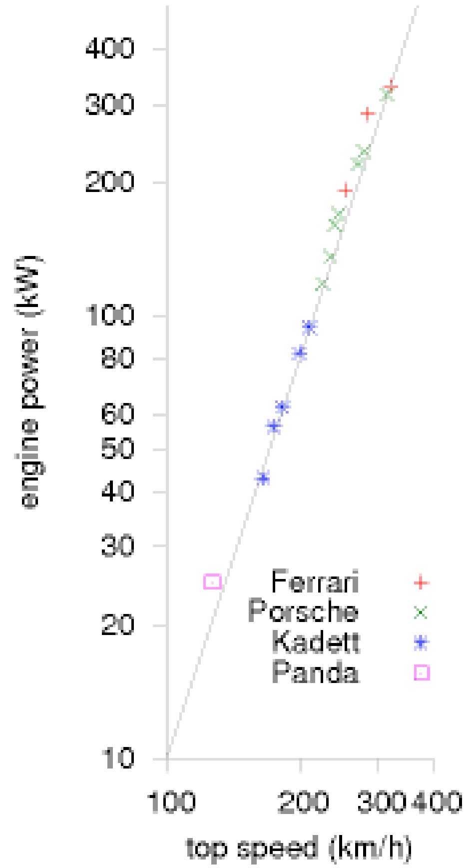


Figure A.13. Powers of cars (kW) versus their top speeds (km/h). Both scales are logarithmic. The power increases as the third power of the speed. To go twice as fast requires eight times as much engine power. From Tennekes (1997).

P proportional to v^3 seems reasonable even for real engines.

Cars

For short trips, braking dominates, while for long trips air resistance is more important.

Comparing factors,

If $m_c > \rho A d$, then braking is more important.

mass of car   mass of air in tube

From this we can calculate the threshold distance between stops separating "city" and "highway" driving.

$$\boxed{d^* = \frac{m_c}{\rho A_{car} c_d}}$$

Typical value around 750 m.

Cars

To reduce vehicle power consumption:

(braking dominated)	(drag dominated)
1. Reduce mass of car	1. Reduce drag coefficient
2. Regenerative brakes	2. Reduce frontal area
3. Reduce speed	3. Reduce speed

Overall vehicle efficiency in power use is around 25%, so power consumption figures need to be multiplied by a factor of 4.

Cars

(3) Inefficiency

A. Thermodynamic limit on engine efficiency

B. Other factors

Cars

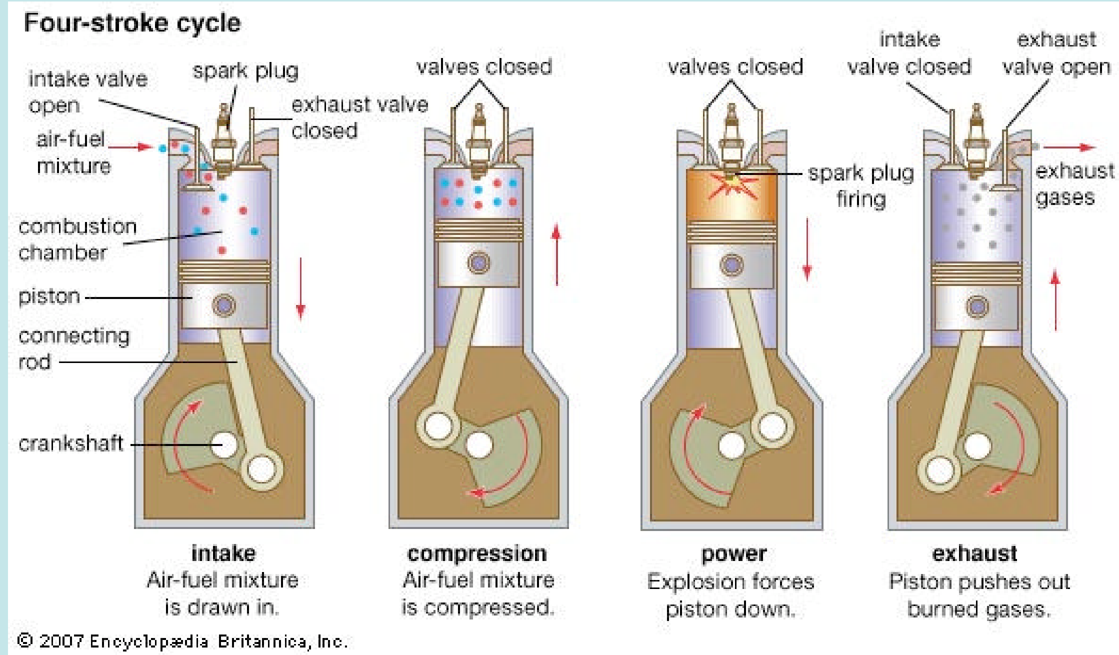
Internal combustion engine

Otto vs Diesel

Spark ignition

Compression ignition

Cars


Four-stroke cycle
intake valve open
spark plug
air-fuel mixture
exhaust valve closed
combustion chamber
piston
connecting rod
crankshaft
valves closed
valves closed
spark plug firing
intake valve closed
exhaust valve open
exhaust gases
intake
Air-fuel mixture is drawn in.
compression
Air-fuel mixture is compressed.
power
Explosion forces piston down.
exhaust
Piston pushes out burned gases.
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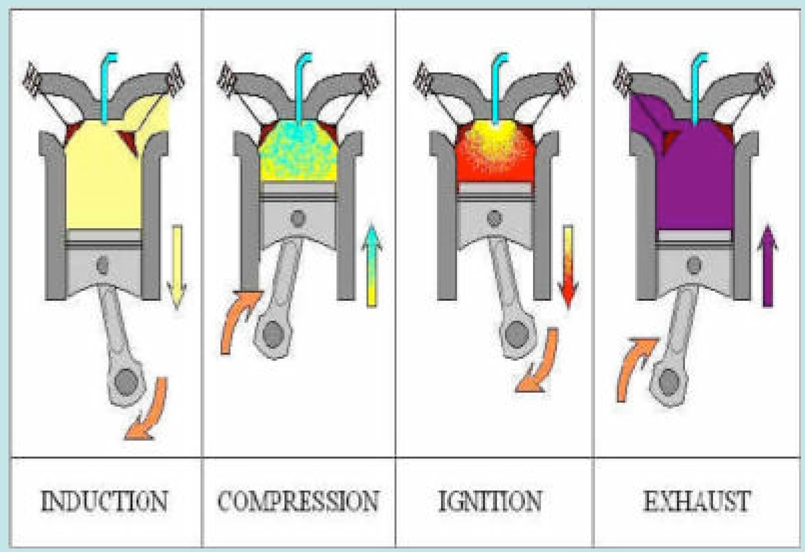
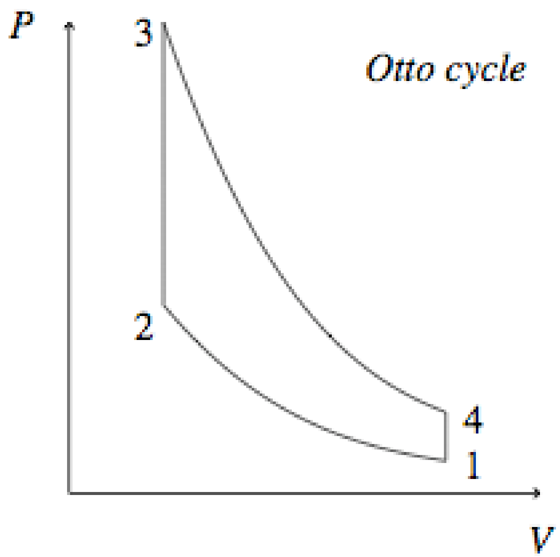
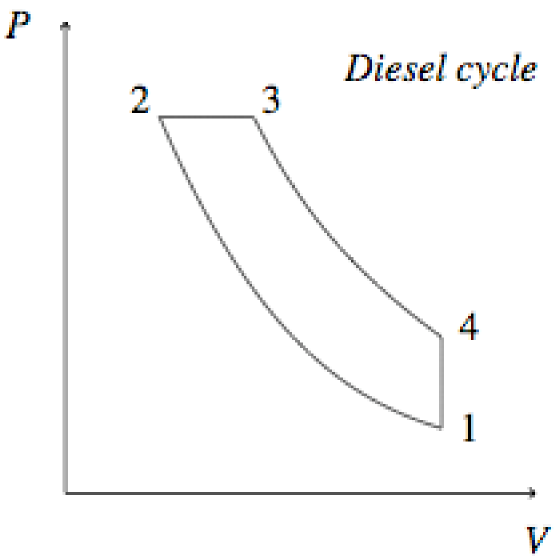

INDUCTION
COMPRESSION
IGNITION
EXHAUST

Cars - thermodynamic perspective





Theoretical efficiency:

$$\eta = \frac{r^{\gamma-1} - 1}{r^{\gamma-1}}$$

Theoretical efficiency:

$$\eta = 1 - r^{\gamma-1}\left(\frac{\alpha^{\gamma} - 1}{\gamma(\alpha - 1)}\right)$$

(see handout for definitions)

Cars

For the same compression ratio, the Otto cycle is more efficient.

However, diesel engines typically operate at higher compression ratios (20:1 rather than 10:1), making them slightly more efficient overall.

Typical efficiency is around 0.46 for Otto cycle.

Other factors in energy loss: friction, turbulence, drivetrain inefficiency, use of engine power for water pump and electrical generator.

Cars (4) Rolling resistance

wheel	C_{rr}
train (steel on steel)	0.002
bicycle tyre	0.005
truck rubber tyres	0.007
car rubber tyres	0.010

Table A.8. The rolling resistance is equal to the weight multiplied by the coefficient of rolling resistance, C_{rr}. The rolling resistance includes the force due to wheel flex, friction losses in the wheel bearings, shaking and vibration of both the roadbed and the vehicle (including energy absorbed by the vehicle's shock absorbers), and sliding of the wheels on the road or rail. The coefficient varies with the quality of the road, with the material the wheel is made from, and with temperature. The numbers given here assume smooth roads. [2bhu35]

Rolling resistance is due to friction, and is velocity-independent.

$$F = c_{rr}mg \begin{cases} \text{-about 100 N/ton} \\ \text{-(equivalent to climbing a 1\% gradient).} \end{cases}$$

E/d = F x d/d = F = Pxt/d = P/v   i.e. E/d is a *force*

RR exceeds air resistance when $c_{rr}mg = \frac{1}{2}\rho c_d A v^2$

Cars (vs. bikes and trains)

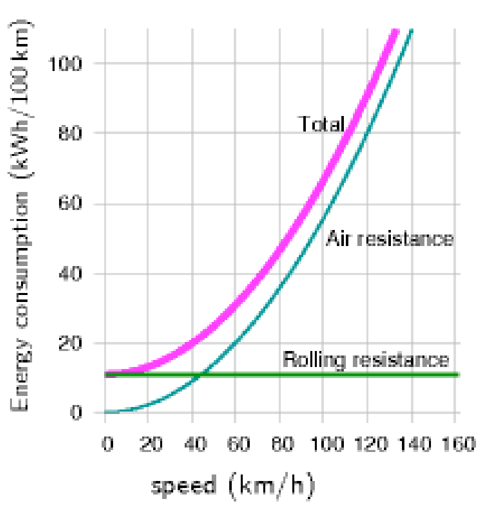


Figure A.9. Simple theory of car fuel consumption (energy per distance) when driving at steady speed. Assumptions: the car's engine uses energy with an efficiency of 0.25, whatever the speed; $c_d A_{car} = 1\ m^2$; $m_{car} = 1000$ kg; and $C_{rr} = 0.01$.

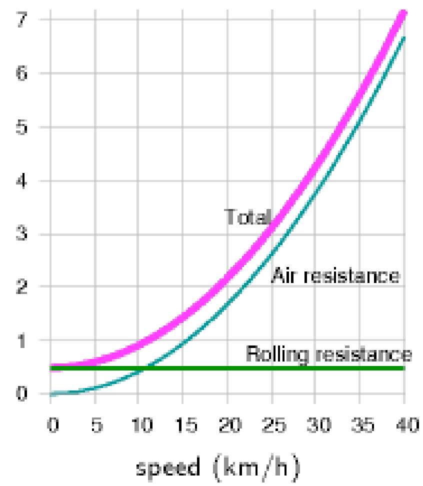


Figure A.10. Simple theory of bike fuel consumption (energy per distance). Vertical axis is energy consumption in kWh per 100 km. Assumptions: the bike's engine (that's you!) uses energy with an efficiency of 0.25,; the drag-area of the cyclist is $0.75\ m^2$; the cyclist+bike's mass is 90 kg; and $C_{rr} = 0.005$.

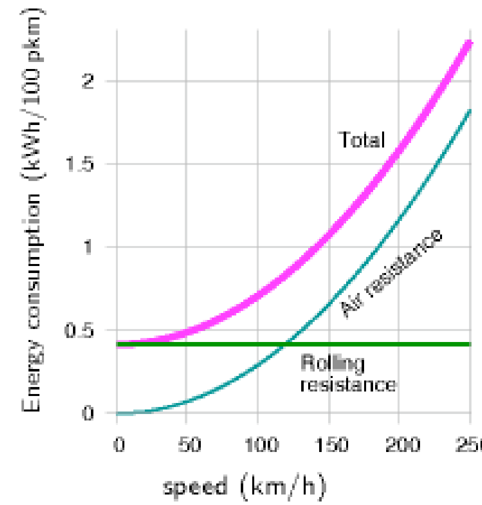


Figure A.11. Simple theory of train energy consumption, per passenger, for an eight-carriage train carrying 584 passengers. Vertical axis is energy consumption in kWh per 100 p-km. Assumptions: the train's engine uses energy with an efficiency of 0.90; $c_d A_{train} = 11\ m^2$; $m_{train} = 400\ 000$ kg; and $C_{rr} = 0.002$.

Cars

Electric cars?

Range limited by energy density of batteries:

Lead-acid: 40 Wh/kg (200 km)

Lithium: 120 Wh/kg (500 km)

100x less than gasoline

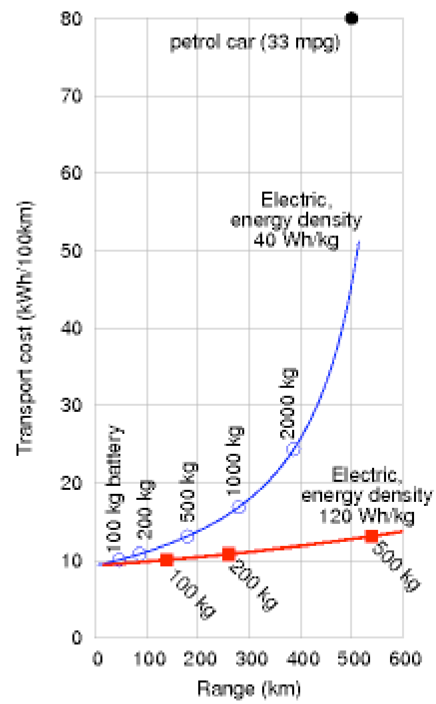
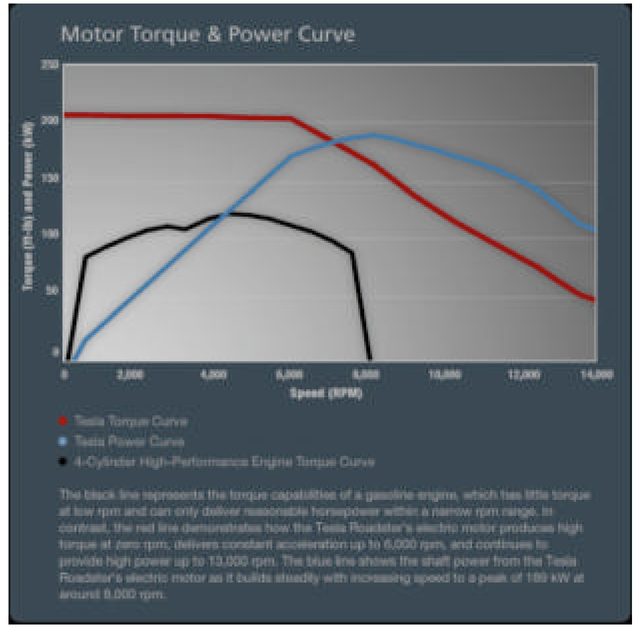


Figure A.14. Theory of electric car range (horizontal axis) and transport cost (vertical axis) as a function of battery mass, for two battery technologies. A car with 500 kg of old batteries, with an energy density of 40 Wh per kg, has a range of 180 km. With the same weight of modern batteries, delivering 120 Wh per kg, an electric car can have a range of more than 500 km. Both cars would have an energy cost of about 13 kWh per 100 km. These numbers allow for a battery charging efficiency of 85%.

Cars

Electric cars have advantages over ICE in terms of torque as well as engine efficiency.

Tesla Roadster



Mackay: Even with "dirty" electrical energy, electric cars are at least as "green" as fossil cars. (Power consumption of 20 kWh/100 km with grid electricity carbon footprint of 500 g/kWh leads to effective emissions of 100 g CO_2/km.