Internal Combustion Engines
I: Fundamentals and Performance Metrics

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2018 Princeton-Combustion Institute
Summer School on Combustion
Course Length: 9 hrs

(Mon.- Wed., June 25-27)

Short course outline:

Internal Combustion (IC) engine fundamentals and performance metrics, computer modeling supported by in-depth understanding of fundamental engine processes and detailed experiments in engine design optimization.

Day 1 (Engine fundamentals)

Hour 1: IC Engine Review, Thermodynamics and 0-D modeling
Hour 2: 1-D modeling, Charge Preparation
Hour 3: Engine Performance Metrics, 3-D flow modeling

Day 2 (Computer modeling/engine processes)

Hour 4: Engine combustion physics and chemistry
Hour 5: Premixed Charge Spark-ignited engines
Hour 6: Spray modeling

Day 3 (Engine Applications and Optimization)

Hour 7: Heat transfer and Spray Combustion Research
Hour 8: Diesel Combustion modeling
Hour 9: Optimization and Low Temperature Combustion

Why have I spent my entire career on IC engine research?
and why should you spend your career on IC engines?

To move people and goods fast, you need fuel and must burn it, preferably efficiently.

Why the reciprocating IC engine?

Many brainstorms/fads have come and gone - reciprocating ICs are still the winners!

- e.g., solar power (1970s) - did not consider small amount of sun energy reaching car roof.

Many transportation engine concepts have failed (or still failing) during my career include:

Sterling engines, Rotary engines, Solar power, Stratified-charge engines, Two-stroke engines, Hydrogen engines, Fuel cell engines, Battery electric vehicle engines…..

Environmental impact of IC engines has been reduced by more than 99% during my career, and is now the least among alternatives:

- e.g., battery electric engines waste more energy/resources and produce equal or more pollution, just at a different location (power station).

But, fossil fuel combustion thought by some to be a cause warming/climate change

However, reputable scientists disagree over causes/extent of climate change.

Summary: We cannot create energy out of nothing:

Fossil fuels have built our world - no better alternative has emerged yet.

Energy is required to maintain our modern quality of life.

Energy use has also become political – research is needed about the long-term influence of all energy technologies (not just IC engines) on our planet.

Motivation

Society relies on IC engines for transportation, commerce and power generation:
utility devices (e.g., pumps, mowers, chain-saws, portable generators, etc.), earth-moving equipment, tractors, propeller aircraft, ocean liners and ships, personal watercraft and motorcycles

ICEs power the 600 million passenger cars and other vehicles on our roads today.
260 million vehicles (cars, buses, and trucks) registered in US alone (2015).

77 million cars were made world-wide in 2016, compared to 40 million in 2000.
China became the world's largest car market in 2011.
A quarter of all cars are produced in the European Union, 50% are powered diesels.
→ IC engine research spans both gasoline and diesel powerplants.

Fuel Consumption

70% of the roughly 96 million barrels of crude oil consumed daily world-wide is used in IC engines for transportation.

10 million barrels of oil are used per day in the US in cars and light-duty trucks
4 million barrels per day are used in heavy-duty diesel engines,
- total oil usage of 2.5 gallons per day per person.

Of this, 62% is imported (at $80/barrel - costs US economy $1 billion/day).

US energy flow chart

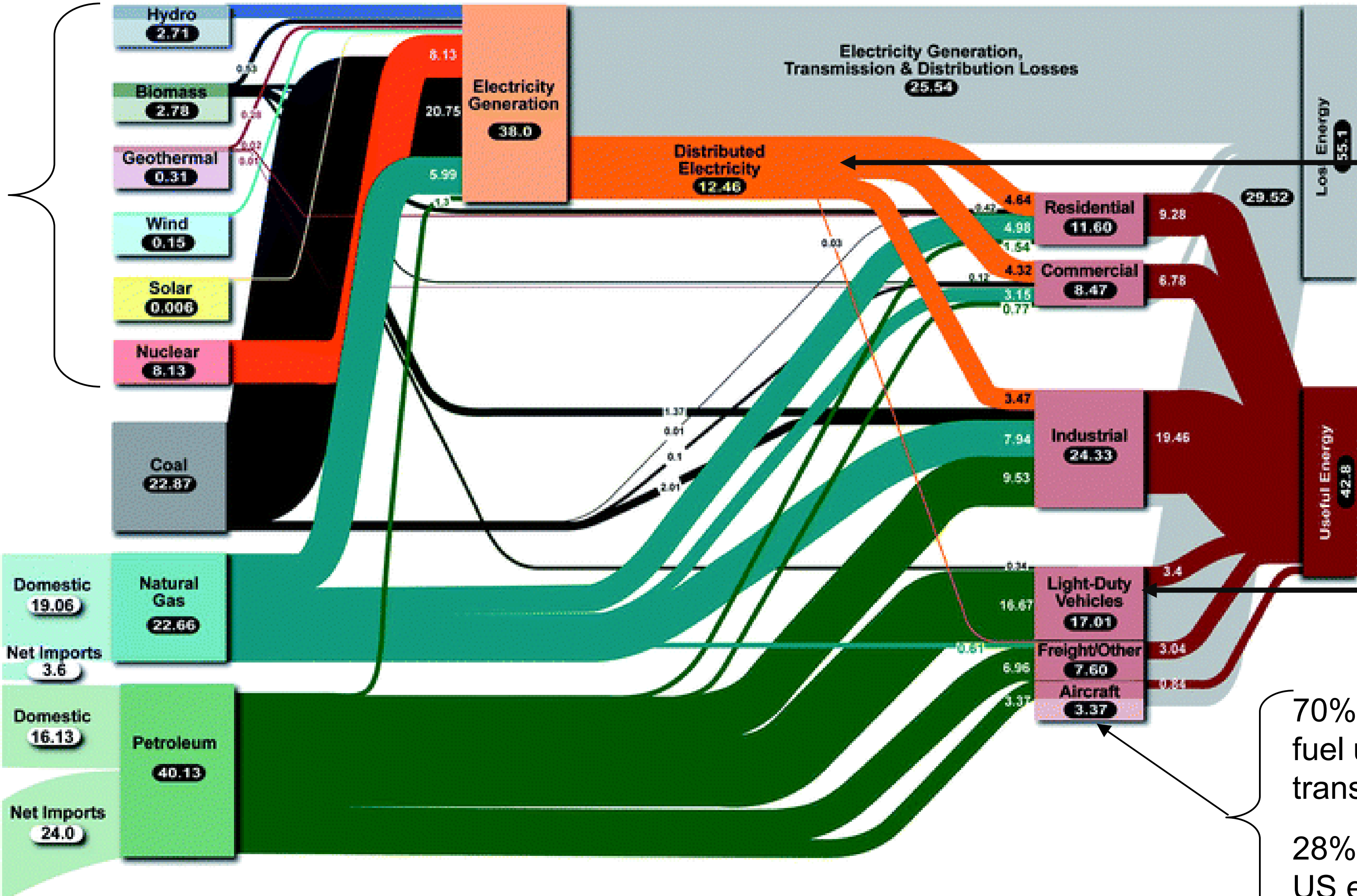
World energy use = 500 x 10^{18} J

14EJ

23EJ

23EJ

40EJ



12.46 → 18.8

70% of liquid fuel used for transportation

28% of total US energy consumption

100x10^{18}J

http://www.eia.gov/totalenergy/

Fuel consumption

World oil use: 96 million bbl/day = 4 billion gal/day (~0.6 gal/person/day)

Why do we use fossil fuels (86% of US energy supply)?

Large amount of energy is tied up in chemical bonds – e.g., Octane:

$C_8H_{18} + 12.5(O_2+3.76N_2) \rightarrow 8CO_2 + 9H_2O+47N_2$ (releases 48 MJ/kg_{fuel})

Kinetic energy of 1,000 kg car at 60 mph (27 m/s)
= $1/2 \cdot 1{,}000 \cdot 27^2$ (m^2 kg/s^2 =Nm) ~0.46 MJ
= energy in 10g gasoline ~ 1/3 oz (teaspoon)

CO_2 emissions - estimate:

1 billion vehicles/engines, say each burns 2 gal/day (1 gal ~ 6.5lb ~ 3kg)

$\rightarrow 6\text{x}10^9$ kg_{fuel}/day*$48\text{x}10^6$ J/kg_{fuel} = $290\text{x}10^{18}$ J/yr

1 kg gasoline makes $8 \cdot 44/114$=3.1 kg CO_2

~ 365 day/yr $\cdot$ $6\text{x}10^9$ kg_{fuel}/day ~ $6.7\text{x}10^{12}$ kg-CO_2/yr ~ 6.7 Gt-CO_2/year

(Humans exhale ~ 1 kg-CO_2/day = $6\text{x}10^9$ kg-CO_2/yr)

Total mass of air in the earth's atmosphere ~ $5\text{x}10^{18}$ kg

CO_2 mass from engines/year added to earth's atmosphere

$6.7\text{x}10^{12}$ / $5\text{x}10^{18}$ = 1.3 ppm/yr ~ 25% of measured

Other sources – agriculture 30%, building (30%),……

Some facts about CO_2 and energy

Total Carbon, Hydrogen and Oxygen on planet earth is fixed, and they participate in a system with sunlight.

Photosynthesis uses sunlight to convert atmospheric CO_2 into HC vegetation.
(Fossil fuel originates from decayed vegetation stored underground eons ago.)

Oxidizing fossil fuel converts previously stored sunlight energy back into CO_2

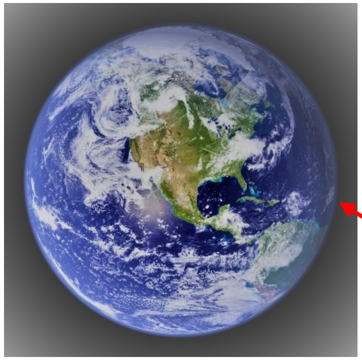
Energy budget - Indiana.edu 2018

Sun's radiation reaches the upper atmosphere at a rate of 1.4 MW/m^2
~ 70% reaches (perpendicularly) ground on a clear day;
~ 30% is scattered back into space (depending on cloud cover (albedo), etc.)
Average surface flux (accounting for night, surface curvature, etc.) is 175 W/m^2

Sun's power available for capture (by plants or solar cells) = $175*4*\pi*r^2$

= 89,300 TW ~ 90 PW

Mankind's total energy consumption rate ~ 15.8 TW



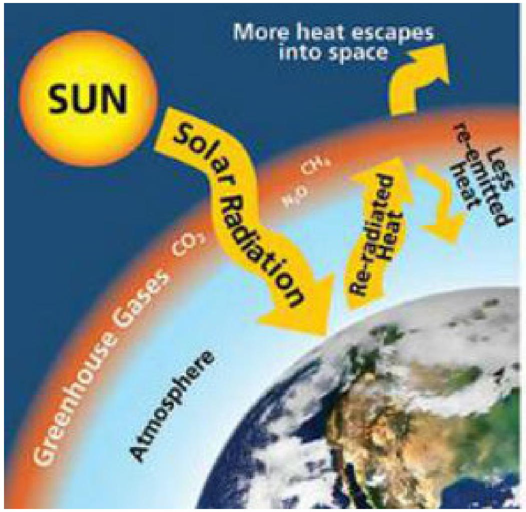
r=6,378 km

<u>0.017%</u> - More energy available from the sun in 1.5 hour than worldwide consumption in 1 year!

Some facts about CO_2 and energy released

Combustion-generated CO_2 – consider methane (CH_4):

4(C-H) + 2(O=O) → O=C=O + 2H-O-H + energy



Energy released from bond energies:

4*411 + 2*494 → 2*799 + 2*(2*460)

→ Rearrangement of bonds releases 806 kJ/mol_{fuel}

→ Most of combustion's energy comes from O_2 → CO_2

C-H and O-H bond energies are similar

1 extra O_2 (0.5 for C_nH_{2n} fuel) goes to water via O-H - as a "catalyst"

Greenhouse gases – H_2O, CO_2, …..

Combustion product gases have dipole absorption bands in the IR

- long wavelength radiation is absorbed and atmosphere is thus heated
- keeps us warm! Air temperature would be -17°C instead of 13°C

Global Warming/Climate Change due to anthropogenic sources

- Atmospheric gases reduce OLR by 30%

Water vapor ~ 66-85% of greenhouse effect
CO_2 ~ 9-26% (depending on humidity)

70% of earth is covered by water
H_2O evaporates (cools); condenses in clouds (heats air) ~ 40PW of energy transfer

Oceans contain most of earth's water - have dominant effect on atmospheric CO_2 levels.
Large ocean thermal inertia stabilizes climate
- most of thermal energy at Earth surface stored in oceans Indiana.edu 2018
- poor understanding of cloud physics is the main uncertainty in climate models Yin, 2017

Outgoing Longwave Radiation calculations	OLR (Wm^{-2}) MIPAS ref. atmosphere
Global (Höpfner, 2012)	
All gases	259.1
No gas	381.5
All w/o H2O	322.8
All w/o CO2	285.9
All w/o O3	266.3
All w/o N2O	261.0
All w/o CH4	261.0
All w/o O2	259.2
All w/o N2	259.3

30%

Other relevant/interesting parameters (Wikipedia, 2018):

Energy stored in the atmosphere – $m_{air}c_p\Delta T$ = 5×10^{18}kg*1.0 KJ/kg-K*30K=150,000EJ
Global precipitation/yr ~ 5×10^{17} kg-H_2O, vs. 6.7×10^{12}kg-CO_2 emitted **(10^5x)**
Natural decay of organics (forests, etc.) release 440 $GtCO_2$, balances new growth
Biosphere - one tree can store 20kg CO_2/yr – 3×10^{12} trees on earth!

Goal of IC engine:

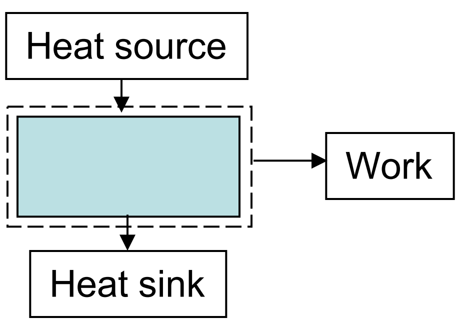
Convert energy contained in a fuel into useful work, as efficiently and cost-effectively as possible.

Identify energy conversion thermodynamics that governs reciprocating engines.
Describe hardware and operating cycles used in practical IC engines.
Discuss approaches used in developing combustion and fuel/air handling systems.

Internal Combustion Engine development
requires control to:
introduce fuel and oxygen, initiate and control combustion, exhaust products

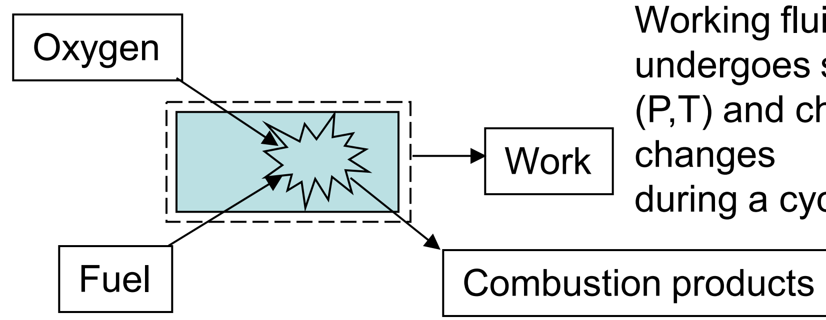
Heat (EC) engine
(Carnot cycle)

Energy release occurs External to the system.
Working fluid undergoes reversible state changes (P,T) during a cycle
(e.g., Rankine cycle)

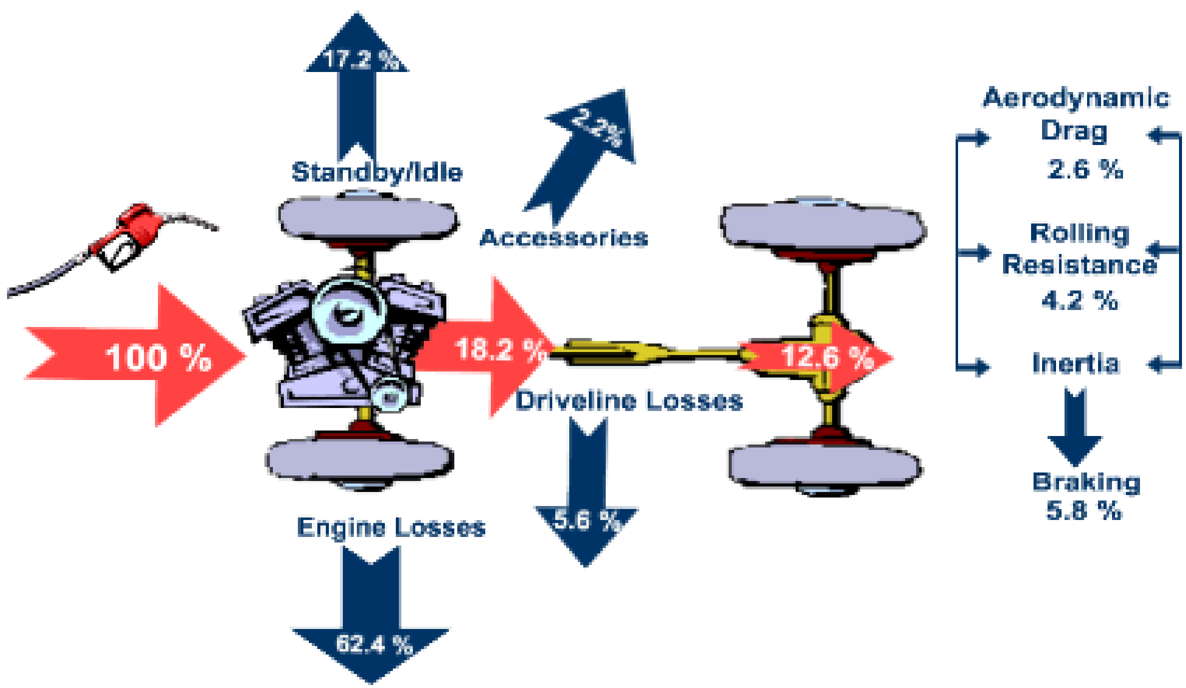


IC engine
(Not constrained by Carnot cycle)

Energy release occurs Internal to the system.
Working fluid undergoes state (P,T) and chemical changes during a cycle



IC Engine Efficiency



Engine Losses – 62.4%

http://www.fueleconomy.gov/feg/atv.shtml

1% (Prof. John Heywood, MIT)

Modern gasoline IC engine vehicle converts about 16% of the chemical energy in gasoline to useful work.

The average light-duty vehicle weighs 4,100 lbs.

The average occupancy of a light-duty vehicle is 1.6 persons.

If the average occupant weighs 160 lbs,

0.16x((1.6x160)/4100) = 0.01

Pollutant Emissions

Combustion of fossil fuels leads to pollutant emissions:
unburned hydrocarbons, CO, nitric oxides (NOx) and particulates (soot).

CO_2 contributes to Green House Gases (GHG), implicated in climate change

CO_2 emissions linked to fuel efficiency:
- automotive diesel engine is 20 to 40% more efficient than SI engine.

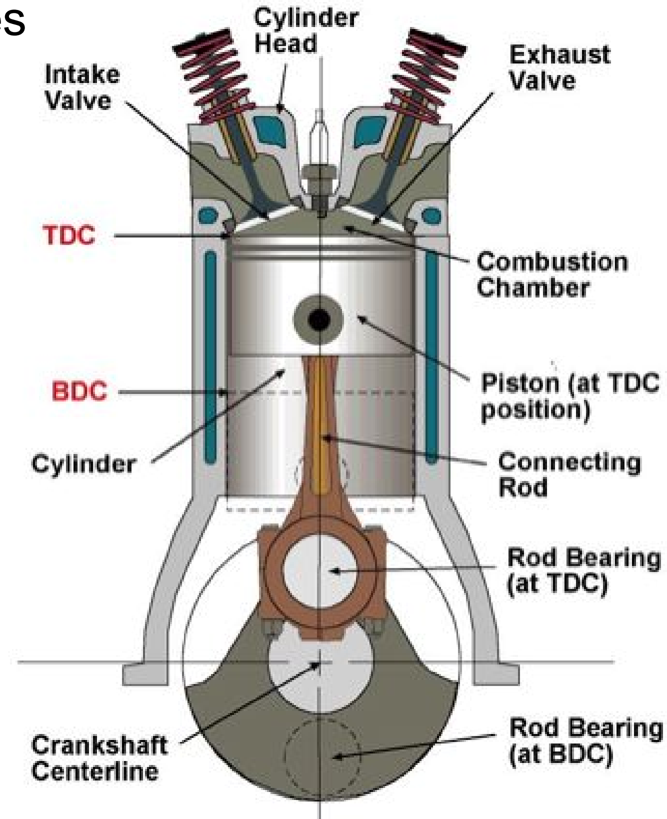
But, diesels have higher NOx and soot.
- serious environmental and health implications,
- governments are imposing stringent vehicle emissions regulations.
- diesel manufacturers use Selective Catalytic Reduction (SCR) after-treatment for NOx reduction: requires reducing agent (urea - carbamide) at rate (and cost) of about 1% of fuel flow rate for every 1 g/kWh of NOx reduction.

Soot controlled with Diesel Particulate Filters (DPF),
- requires periodic regeneration by richening fuel-air mixture to increase exhaust temperature to burn off the accumulated soot
- imposes about 3% additional fuel penalty.

Need for emissions control removes some of advantages of the diesel engine
- VW NOx emissions scandal!

Components of piston engine

Piston moves between Top Dead Center (TDC) and Bottom Dead Center (BDC).
Compression Ratio = CR = ratio of BDC/TDC volumes
Stroke = S = travel distance from BDC to TDC
Bore = B = cylinder diameter
D = Displacement = (BDC-TDC) volume.# cylinders
= π B^2 S/4 . # cylinders



Basic Equations

$P = W$. N = T . N
P [kW] = T [Nm].N [rpm].1.047x10^{-4}

BMEP = P.(rev/cyc) / D . N
BMEP [kPa] = P [kW].(2 for 4-stroke) x10^3 / D [l]. N [rev/s]

BSFC = $\dot{m}_{fuel}$ [g/hr] / P [kW]

Brake = gross indicated + pumping + friction
= net indicated + friction

P = (Brake) Power [kW]
T = (Brake) Torque [Nm] = Work = W
BMEP = Brake mean effective pressure
$\dot{m}_{fuel}$ = fuel mass flow rate [g/hr]
BSFC = Brake specific fuel consumption

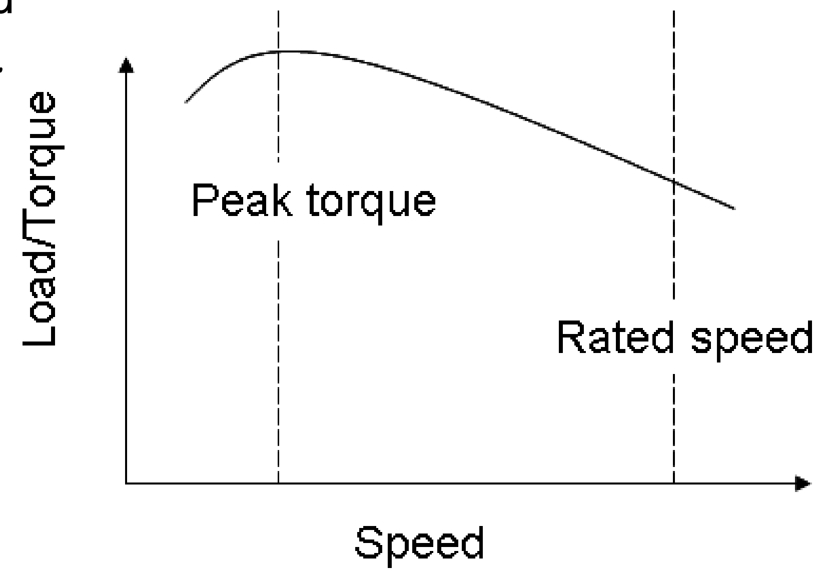
Engine Power

Heywood, 1988

Indicated power of IC engine at a given speed is proportional to the air mass flow rate, $\dot{m}_{air}$

$$P = \eta_f \,.\, \dot{m}_{air}\, N.\, LHV \,.\, (F/A) \,/\, n_r$$

η_f = fuel conversion efficiency
LHV = fuel lower heating value
F/A fuel-air ratio m_f/m_{air}
n_r = number of power strokes / crank rotation
= 2 for 4-stroke



Efficiency estimates:

$$\left.\begin{array}{ll} \text{SI:} & 270 < bsfc < 450 \text{ g/kW-hr} \\ \text{Diesel:} & 200 < bsfc < 359 \text{ g/kW-hr} \end{array}\right\}$$

η_f = 1/46 MJ/kg / 200 g/kW-hr = 40-50%

→500 MW GE/Siemens combined cycle gas turbine natural gas power plant ~ 60% efficient


SGT5-8000H ~530MW

4-stroke (Otto) cycle

1. Intake:
piston moves from TDC to BDC with the intake valve open, drawing in fresh reactants

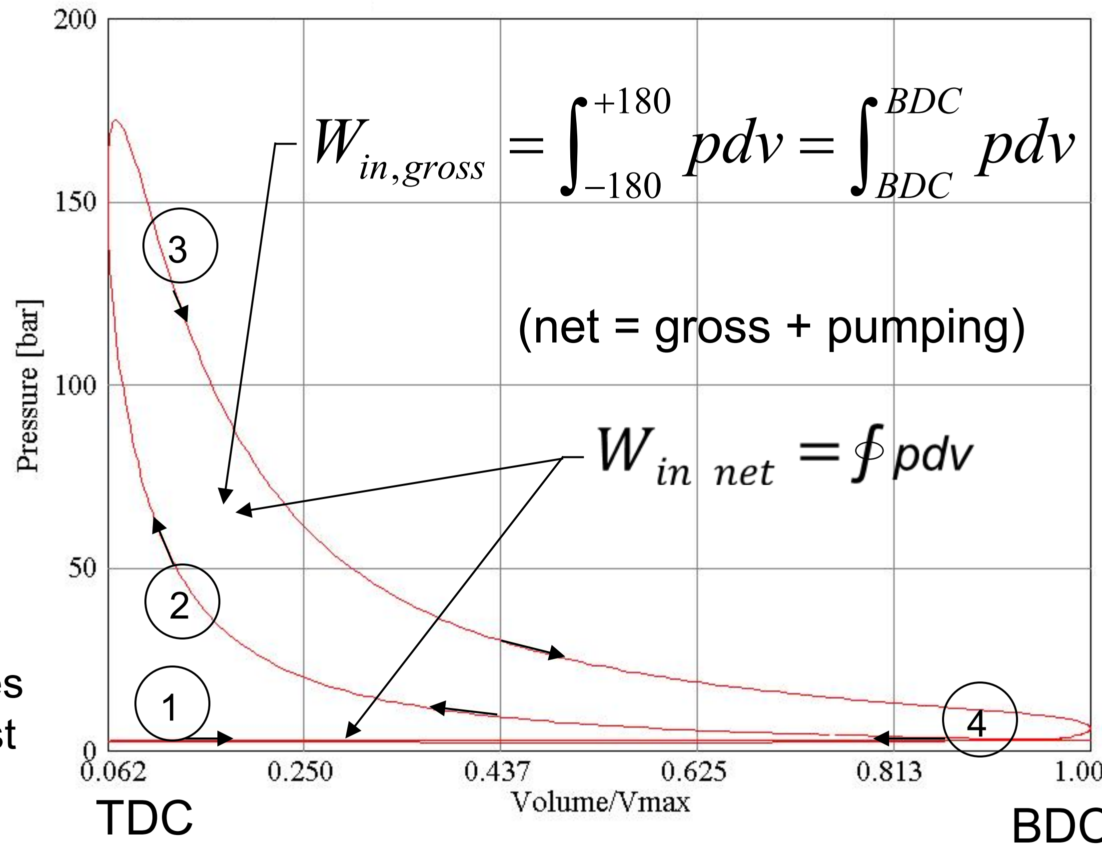
2. Compression:
valves are closed and piston moves from BDC to TDC,
Combustion is initiated near TDC

3. Expansion:
high pressure forces piston from TDC to BDC, transferring work to crankshaft

4. Exhaust:
exhaust valve opens and piston moves from BDC to TDC pushing out exhaust

1,4 Pumping loop – An additional rotation of the crankshaft used to:
- exhaust combustion products
- induct fresh charge

"Suck, squeeze, bang, blow"

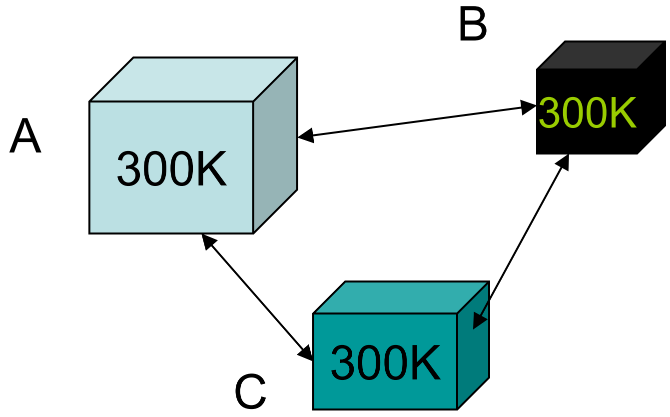


Four-stroke diesel pressure-volume diagram at full load

Heywood, 1988

Thermodynamics review – Zero'th law

1. Systems in thermal equilibrium are at the same temperature
2. If two thermodynamic systems are in thermal equilibrium with a third, they are also in thermal equilibrium with each other.

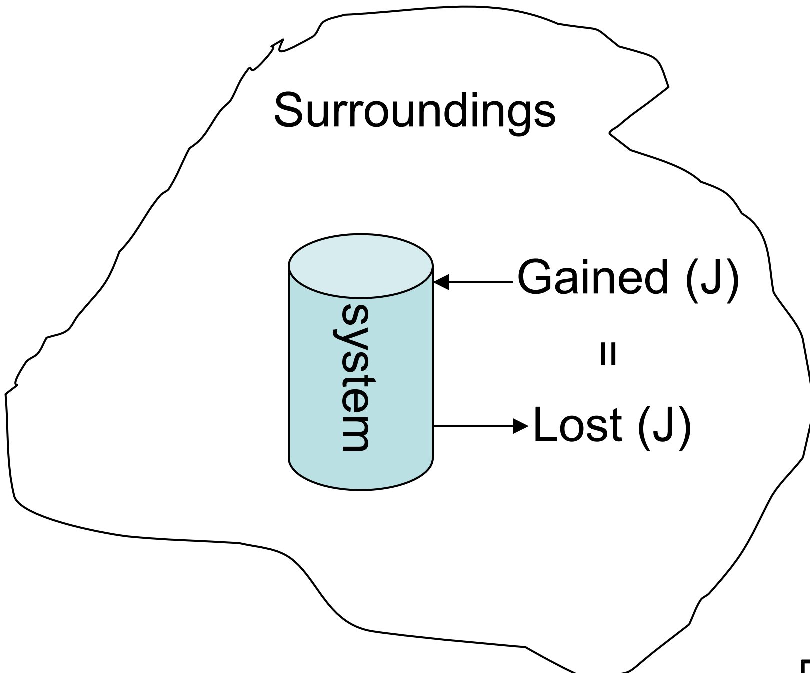


Thermal equilibrium

Heywood, 1988

Thermodynamics review - First law

During an interaction between a system and its surroundings, the amount of energy gained by the system must be exactly equal to the amount of energy lost by the surroundings



Engine System

Gained (input) (J)	Lost (output) (J)
Intake flow	- **Work**
Energy of fuel combustion	+ **Heat Lost (Cylinder wall, Exhaust gas)**
	Friction

$$\boxed{de = dq - dw}$$

Thermodynamics review - Second law

Heywood, 1988

The second law asserts that energy has quality as well as quantity (indicated by the first law)

$$ds = \frac{\delta q}{T} + ds_{irrev}$$

$$ds_{irrev} \geq 0$$

Engine research:

Reduce irreversible losses → Increase thermal efficiency

Equations of State

Heywood, 1988

Thermal: $Pv = RT$ where $R = R_u / W$

Caloric: $de = c_v dT$ and $dh = c_p dT$

Enthalpy: $h = e + Pv$

Ratio of specific heats: $\gamma = \dfrac{c_p}{c_v}$ $\boxed{c_v = \dfrac{R}{\gamma - 1}}$ $\boxed{c_p = \dfrac{\gamma R}{\gamma - 1}}$

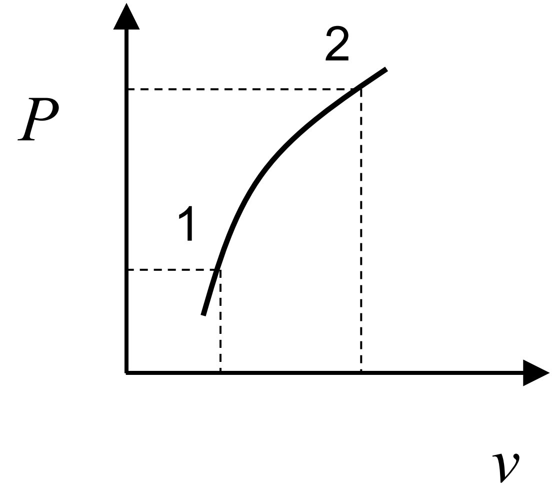
Calculation of Entropy

Gibbs' equation: $\boxed{Tds = de - vdP}$

and

$$s_2 - s_1 = c_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$$

$$s_2 - s_1 = c_v \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1}$$



Isentropic process

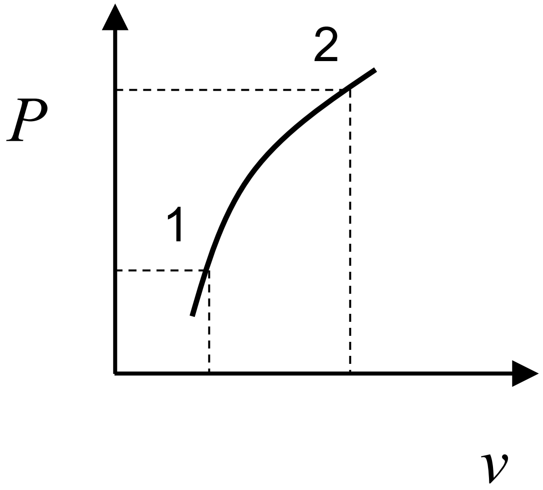
Heywood, 1988

Adiabatic, reversible ideal reference process

$$0 = s_2 - s_1 = c_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$$

$$\boxed{\frac{p_2}{p_1} = \left(\frac{v_1}{v_2}\right)^{\gamma} = \left(\frac{T_2}{T_1}\right)^{\gamma/(\gamma-1)}}$$

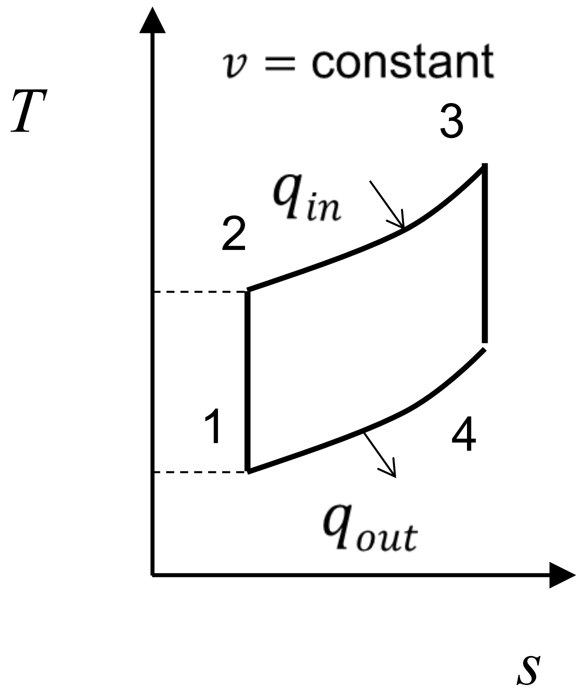
$$0 = s_2 - s_1 = c_v \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1}$$



Ideal cycles

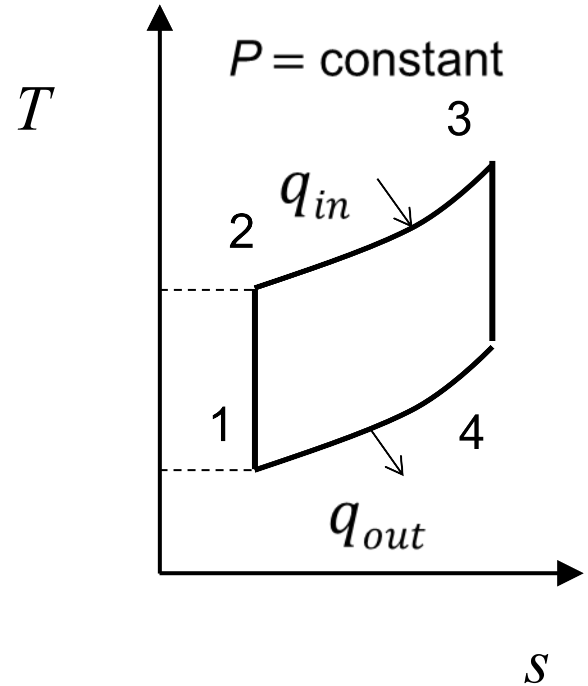
Heywood, 1988

Otto



1-2 Isentropic compression 2-3 Constant volume heat addition 3-4 Isentropic expansion 4-1 Constant volume heat rejection

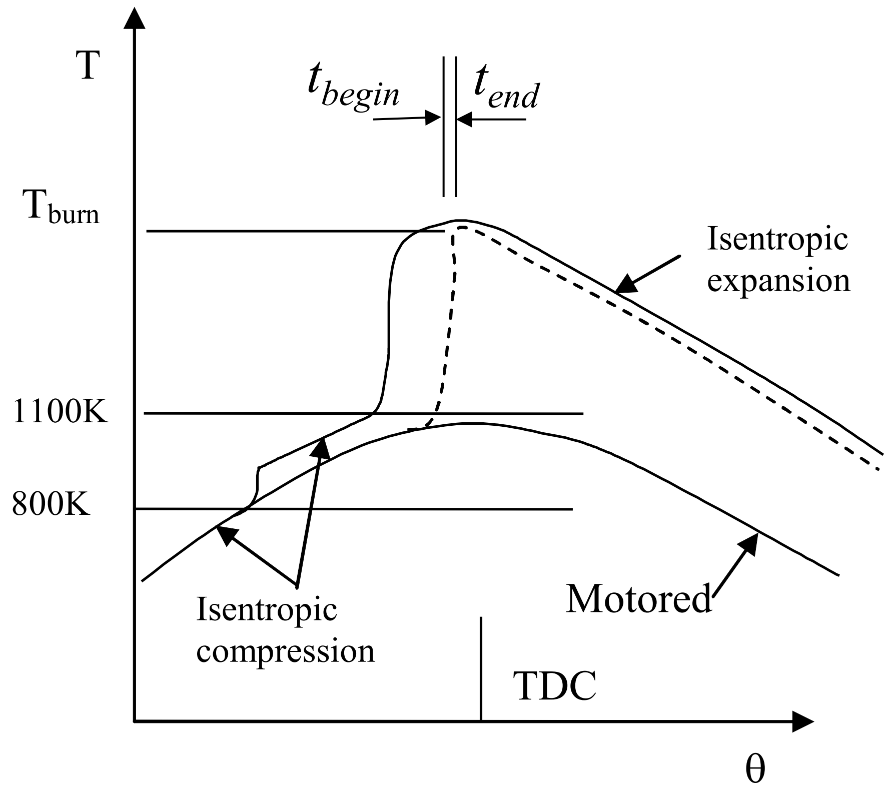
Diesel

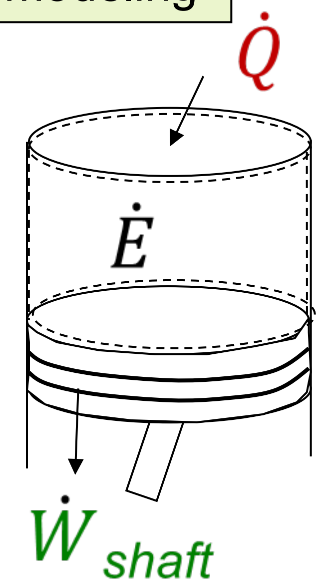


1-2 Isentropic compression 2-3 Constant pressure heat addition 3-4 Isentropic expansion 4-1 Constant volume heat rejection

Constant volume combustion - HCCI:

$$d\dot{E} = d\dot{Q} - d\dot{W}_{shaft}$$





During constant volume combustion process:

$$t_{begin} - t_{end} \longrightarrow 0$$

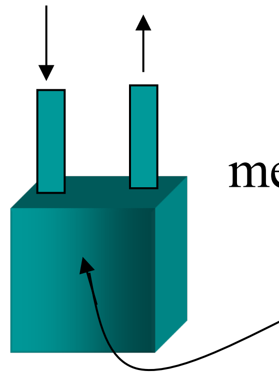
$$\dot{W}_{Shaft} = \int_{t_{begin}}^{t_{end}} P d\forall = 0$$

$$Q = \int_{t_{begin}}^{t_{end}} \dot{Q}\, dt = m_f \cdot Q_{LHV}$$

$$T_{burn} = T_{unburn} + {}^{(\gamma - 1)}\!/_{R}\, m_f Q_{LHV}$$

Zero-Dimensional models

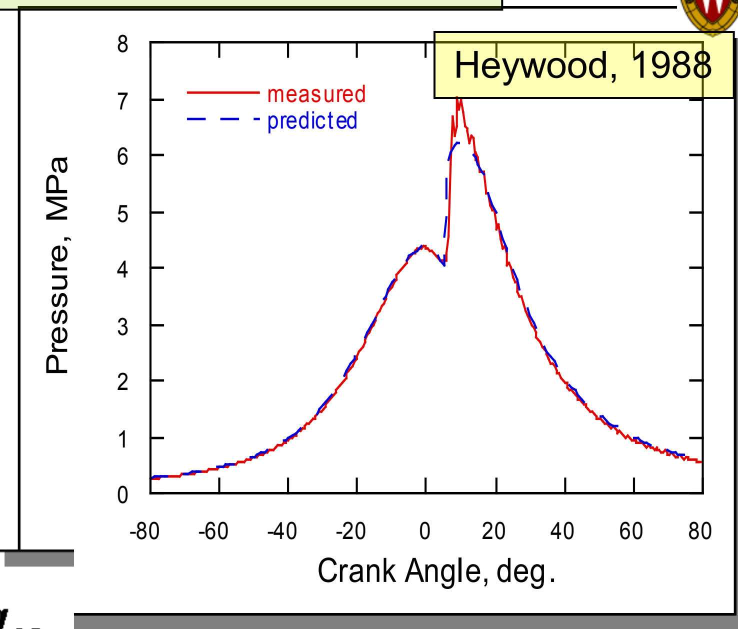
Single zone model



measure

$p(\theta)$

$V(\theta)$



1st Law of Thermodynamics

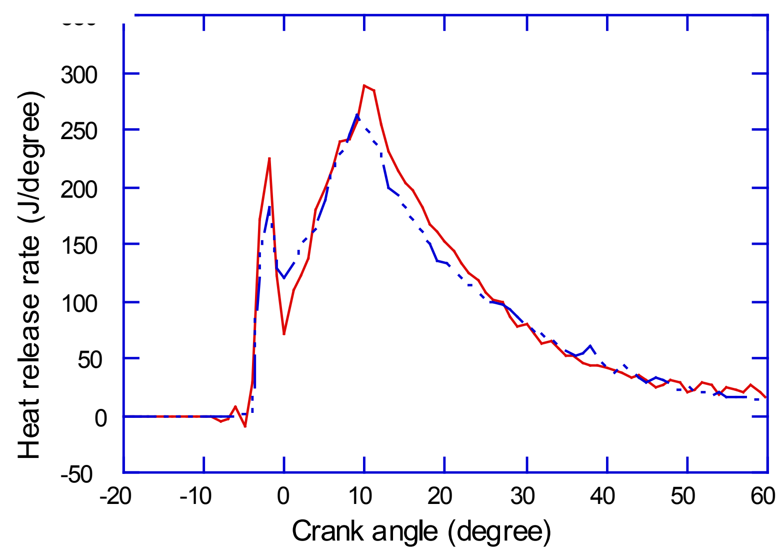
$$mc_v \frac{dT}{dt} + p\frac{dV}{dt} + \sum_j \dot{m}_j h_j = q_{Comb} - q_{Loss} = q_{Net}$$

Use the ideal gas equation to relate p & V to T

$$q_{Net} = p\frac{dV}{dt} + \frac{1}{\gamma - 1}\frac{dpV}{dt}$$

where $$q_{Loss} = hA(T - T_{wall})$$

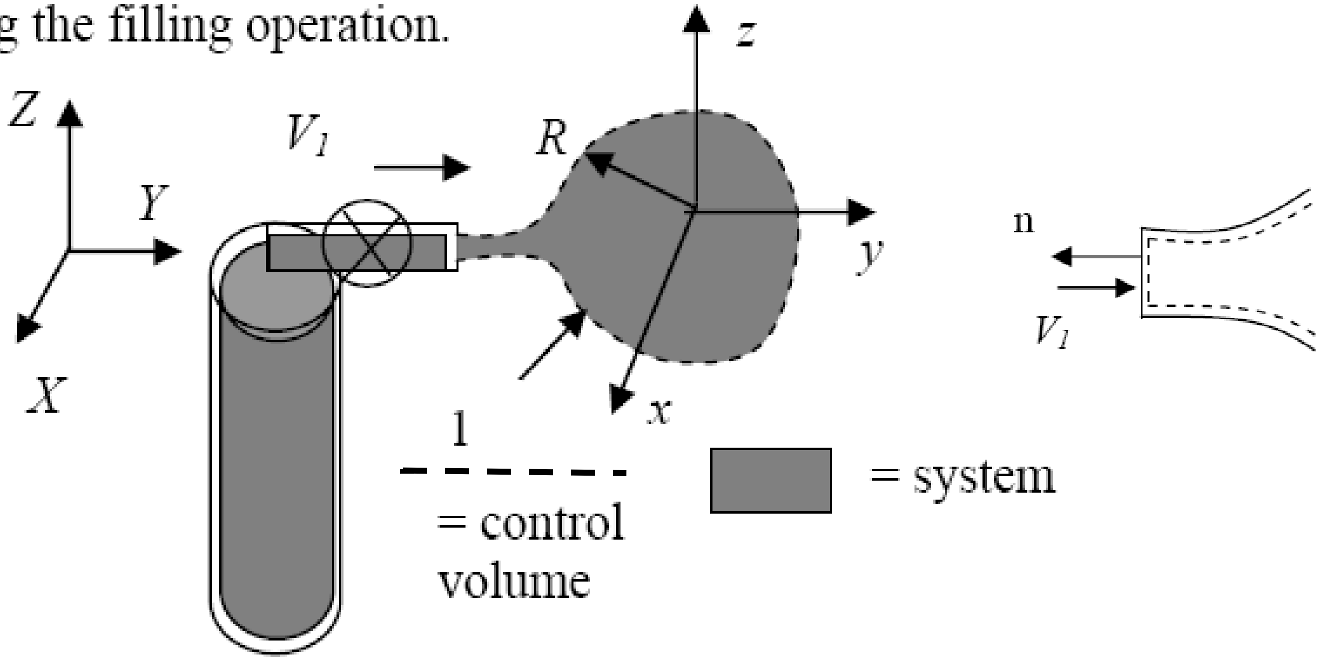
Assume h and T_{wall}



Control volumes and systems

Anderson, 1990

Fluid enters a balloon at the valve (Station 1) at velocity V1 and the control volume deforms during the filling operation.



The Reynold's Transport Equation written for a coordinate system placed on the balloon (xyz) becomes

$$\left.\frac{dM}{dt}\right)_{system} = \frac{d}{dt}\int_{cv}\rho d\forall + \int_{cs}\rho \mathbf{V}_{rel}\cdot\mathbf{n}\, dA = 0$$

$$\boxed{\frac{d}{dt}\left(\rho\frac{4}{3}\pi R^3\right) = \rho_1 V_1 A_1.}$$

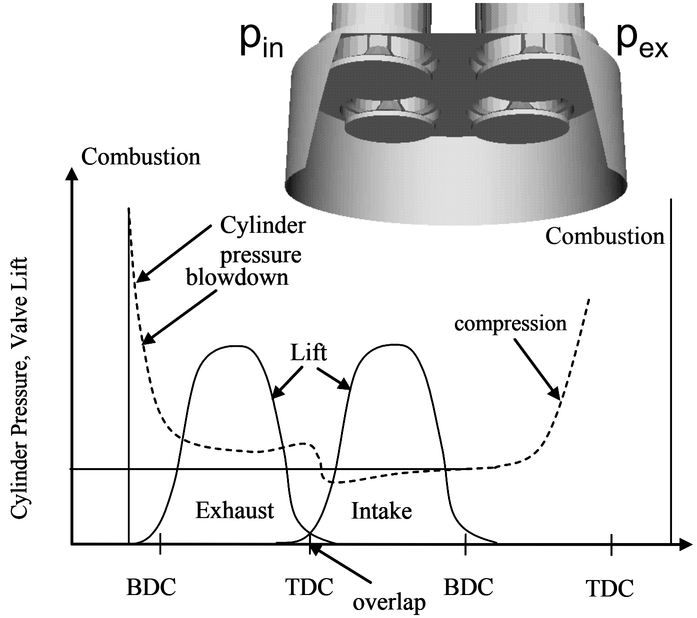
Gas exchange – volumetric efficiency, η_v

Engine intake system:
air filter, carburetor and throttle plate or port fuel injector, intake manifold, intake port, intake valves.

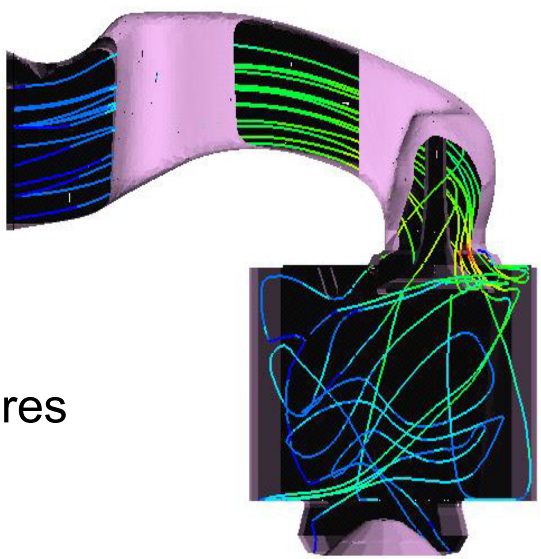
Supercharging – increases inducted air mass (in both gasoline and diesel engines).
Intake and exhaust manifold designed to maximize cylinder filling and scavenging.

Intake system pressure drops (losses) occur due to quasi-steady effects (e.g., flow resistance), and unsteady effects (e.g., wave action in runners).

Engine breathing affected by intake/exhaust valve lifts and open areas (most of the losses).
Valve overlap can cause exhaust gases to flow back into intake system, or intake gases can enter the exhaust (depending on p_{in}/ p_{ex})

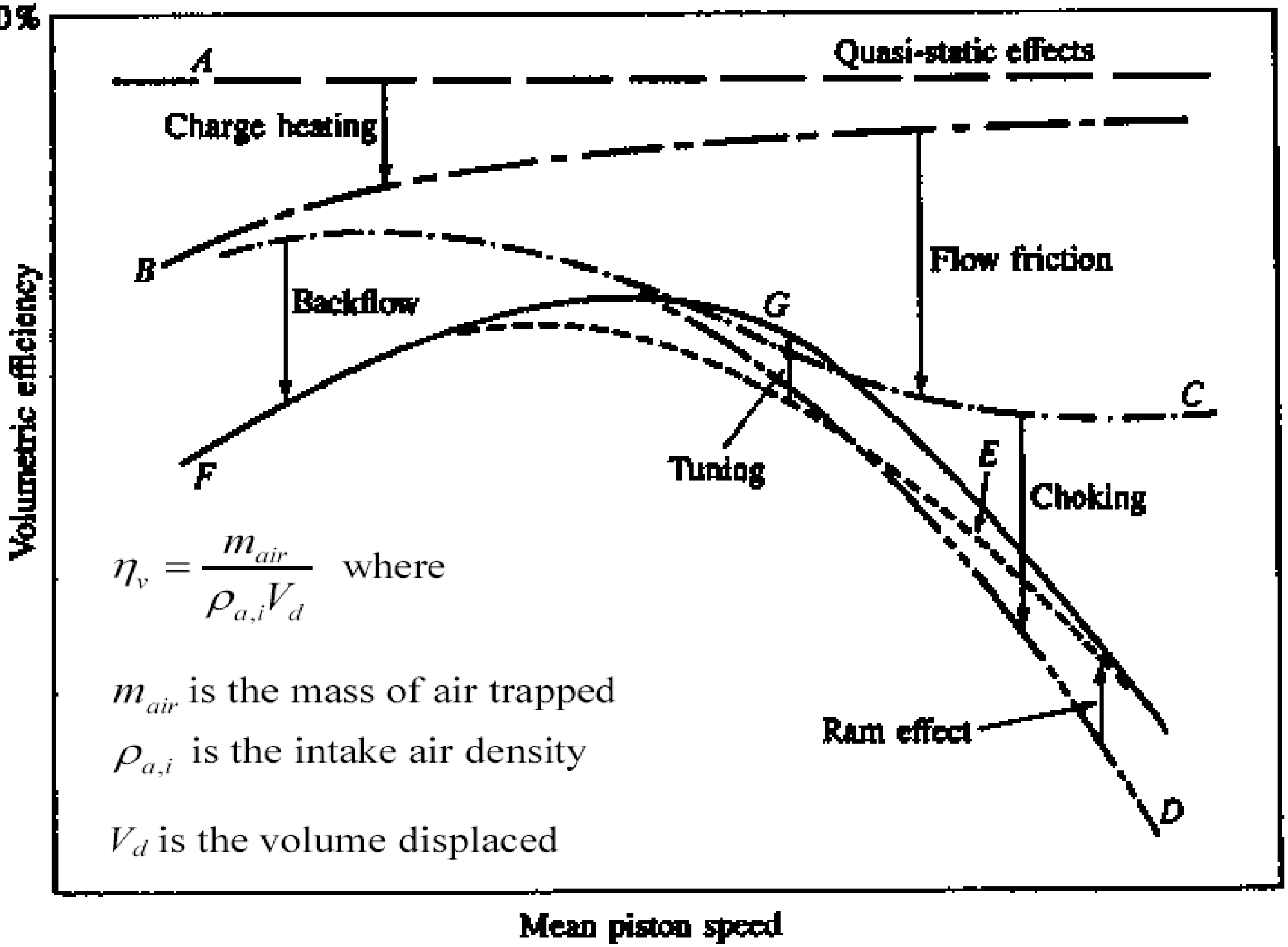


In addition to η_v, intake generates large scale flow structures
- used to promote turbulent mixing
- requires 3-D CFD modeling



Volumetric efficiency parameters (SI engine < CI engine)

Heywood, Fig. 6.9



$$\eta_v = \frac{m_{air}}{\rho_{a,i} V_d} \quad \text{where}$$

m_{air} is the mass of air trapped

$\rho_{a,i}$ is the intake air density

V_d is the volume displaced

A → B → C → D → E → F → G

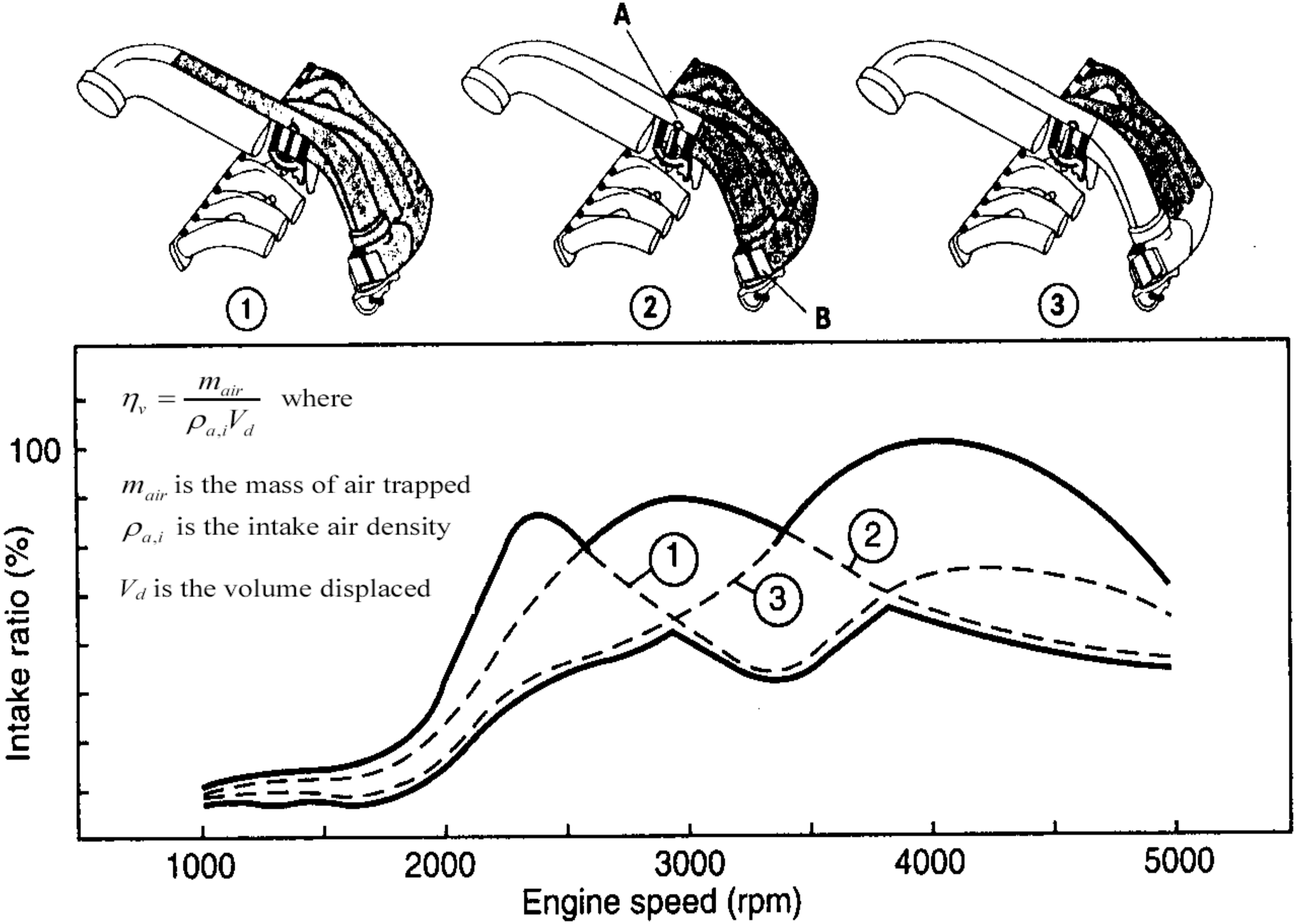
Losses in Carburetor, Intake manifold heating (rho), Fuel vapor displaces air

MAP Pin~Pex in diesel

Lower CR - SI more residual

Diesel - more residual is air

Optimization: Volumetric efficiency



Mercedes-Benz three stage resonance intake system

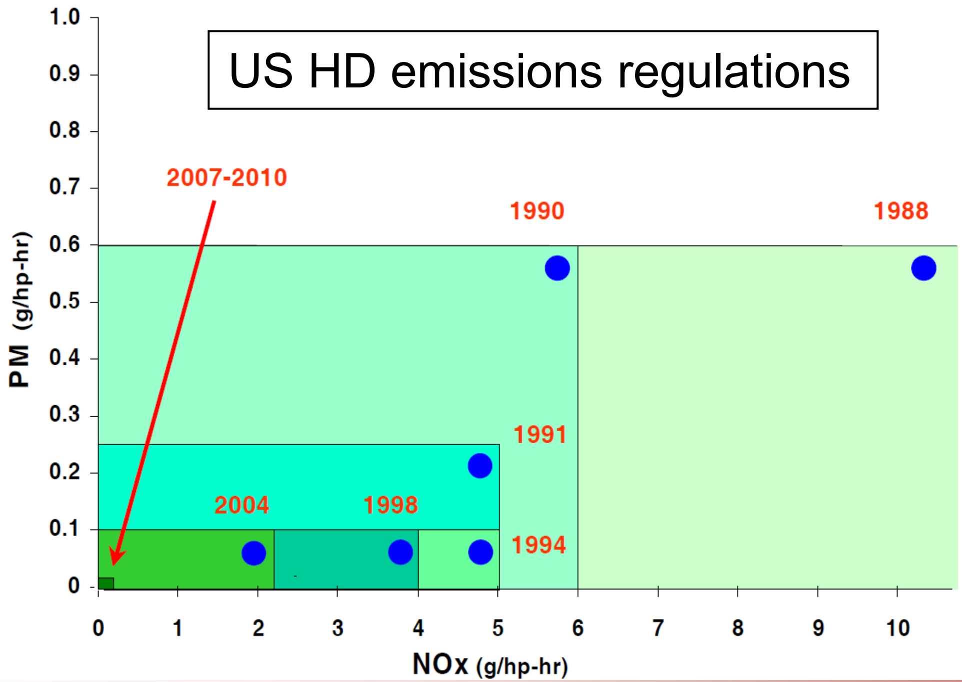
Summary

Transportation is ~1/3 of the total energy use in the US

Internal combustion engines are among the most efficient power plants known to man, but research is needed to improve them further

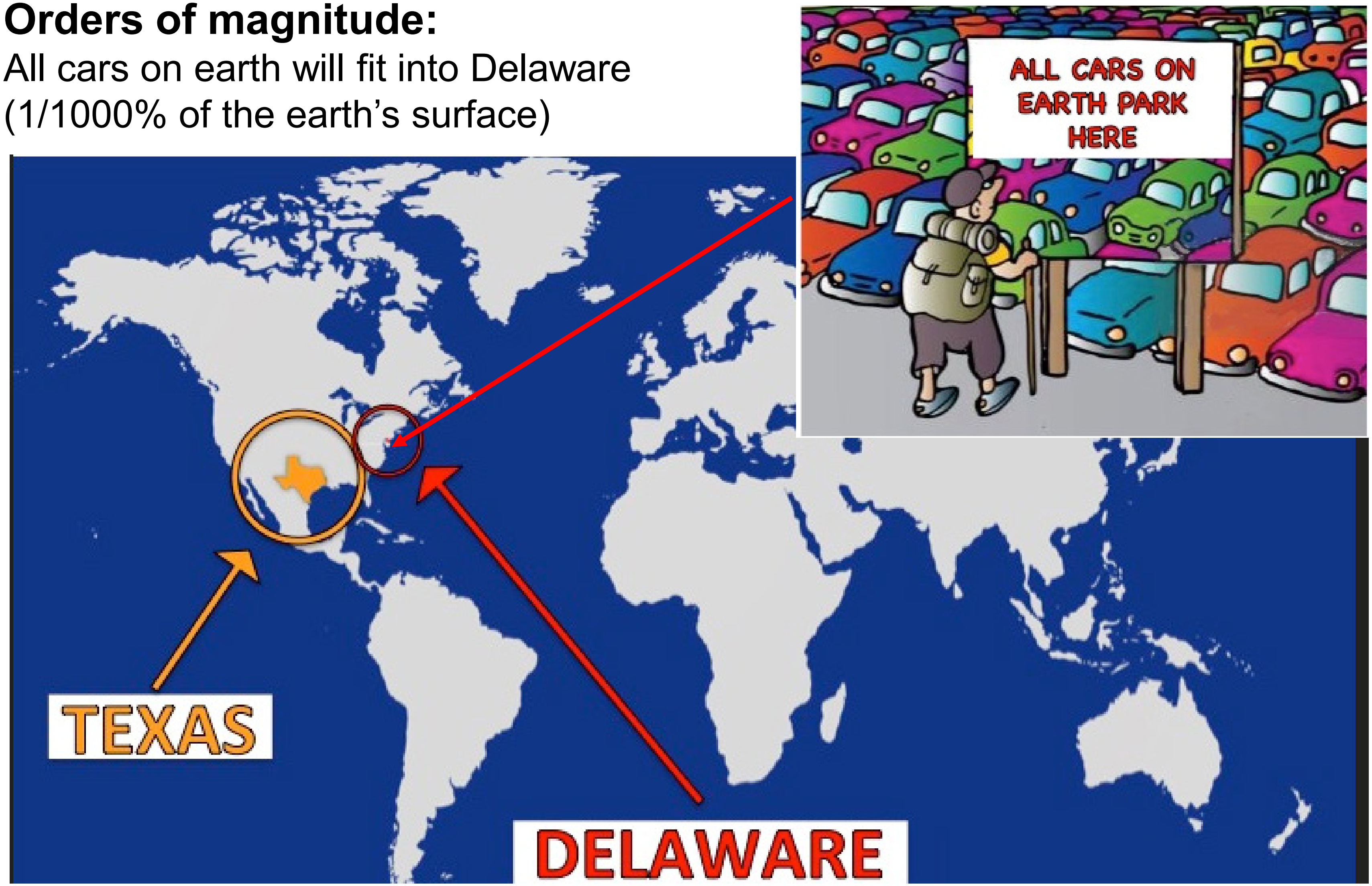
Modeling tools are available to help quantify engine performance and to provide directions for improved efficiency and reduced emissions

The industry faces significant challenges to meet emissions/CO_2 targets,
- great progress has been made in the last 30 years.



Orders of magnitude:

All cars on earth will fit into Delaware
(1/1000% of the earth's surface)



Can a 10^{-5} speck can pollute the entire planet?

References

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