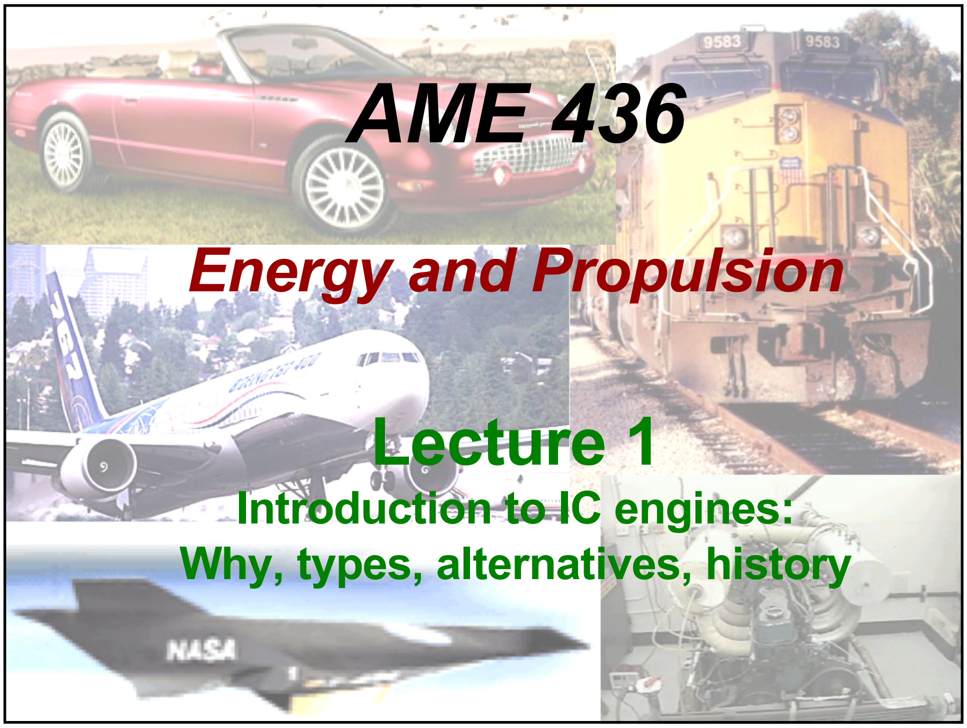

AME 436

Energy and Propulsion

Lecture 1

Introduction to IC engines: Why, types, alternatives, history

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Helpful handy hints

- Download lectures from website before class
- Each lecture includes
  - Outline
  - Beef
  - Examples
  - Summary

  … so make use of these resources!
- Bringing your laptop or tablet allows you to add notes & download files from course website as necessary
- You'll need hard copies for exams since no computers or tablets will be allowed
- Download and install Microsoft Office to view the lecture notes and open the embedded Excel spreadsheets - USC has a site license
- Ask questions in class - the goal of the lecture is to maintain a 2-way "Socratic" dialogue on the subject of the lecture

Nomenclature (summary for whole course)

Symbol	Meaning (units)
A	Cross-section area (m^2)
A^*	Throat area (m^2)
A_e	Exit area (m^2)
ATDC	After Top Dead Center
B	Transfer number for droplet burning (---)
BMEP	Brake Mean Effective Pressure (N/m^2)
BSFC	Brake Specific Fuel Consumption (kg/W)
$BSNO_x$	Brake Specific NO_x (g/kW-hr or kg/J) (similar definition with CO, UHC emissions)
BTDC	Before Top Dead Center
c	Sound speed (m/s)
C	Duct circumference (m)
C_D	Drag coefficient (---)
C_f	Friction coefficient (---)
CO	Carbon monoxide (compound having 1 carbon and 1 oxygen atom)
CM	Control Mass
C_P	Heat capacity at constant pressure (J/kgK)
C_v	Heat capacity at constant volume (J/kgK)
CV	Control Volume
D	Mass diffusivity (m^2/s)
D	Drag force (N)
DORF	Degree Of Reaction Freedom
E	Energy contained by a substance = U + KE + PE (J)
E	Activation Energy (J/mole)

Nomenclature (summary for whole course)

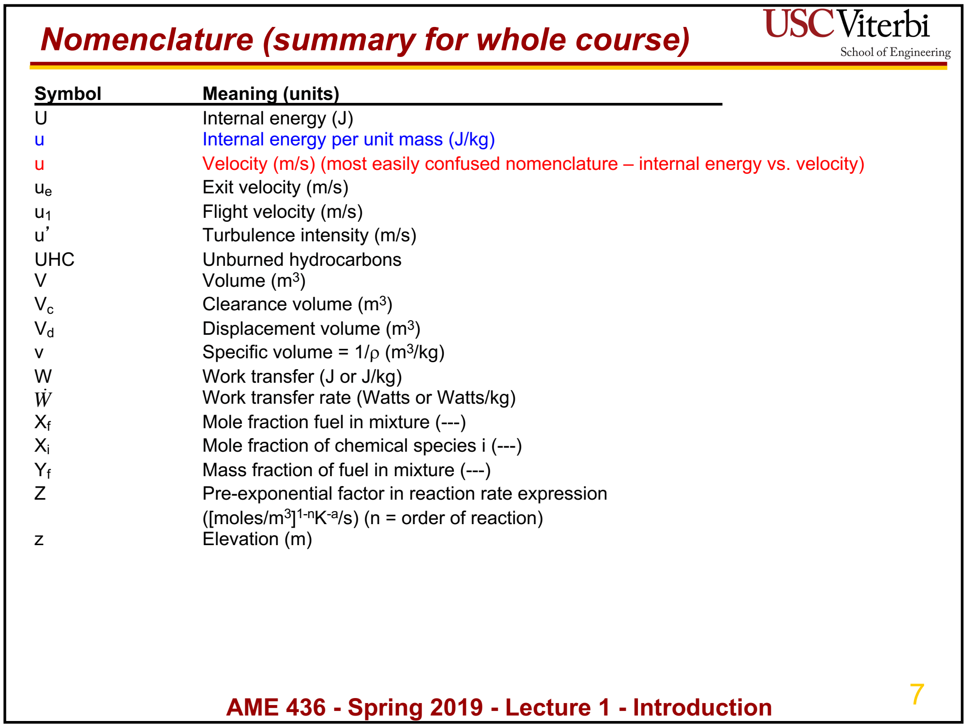
Symbol	Meaning (units)
f	Fuel mass fraction in mixture (---)
FAR	Fuel to air mass ratio (---)
FMEP	Friction Mean Effective Pressure (N/m^2)
g	Acceleration of gravity (m/s^2)
g	Gibbs function ≡ h - Ts (J/kg)
H	Enthalpy ≡ U + PV (J)
h	Enthalpy per unit mass = u + Pv (J/kg)
h	Heat transfer coefficient (usually W/m^2K, dimensionless in AirCycles.xls files)
$\tilde{h}_i$	Enthalpy of chemical species i per mole = $[\tilde{h}(T) - \tilde{h}_{298}]_i + \Delta\tilde{h}^o_{f,i}$ (J/mole)
$[\tilde{h}(T) - \tilde{h}_{298}]_i$	Thermal enthalpy of chemical species i per mole (J/mole)
ICE	Internal Combustion Engine
IMEP	Indicated Mean Effective Pressure (N/m^2)
ISFC	Indicated Specific Fuel Consumption (kg/W)
I_{SP}	Specific impulse (sec)
K_i	Equlibrium constant of chemical species i (---)
k	Thermal conductivity (W/mK)
k	Reaction rate constant ($[moles/m^3]^{1-n}/sec$) (n = order of reaction)
K	Droplet burning rate constant (m^2/s)
Ka	Karlovitz number (= 0.157 $Re_L^{-1/2}(u'/S_L)^2$ for premixed flames in turbulent flows)
KE	Kinetic energy (J or J/kg)
L	Lift force (N)
L_f	Jet flame length (m)
L_I	Integral length scale of turbulence (m)
LOMA	Law Of Mass Action

Nomenclature (summary for whole course)

Symbol	Meaning (units)
M_i	Molecular weight of chemical species i (kg/mole)
M	Mach number (---)
m	mass (kg)
$\dot{m}$	Mass flow rate (kg/sec)
$\dot{m}_a$	Air mass flow rate (kg/s)
$\dot{m}_f$	Fuel mass flow rate (kg/s)
MEP	Mean Effective Pressure (N/m^2)
n	Order of reaction (---)
n	Parameter in MEP definition (= 1 for 2-stroke engine, = 2 for 4-stroke)
n_i	Number of moles of chemical species I
N	Number of chemical species in a mixture
N	Engine rotational speed (revolutions per minute)
NO	Nitric oxide (compound having 1 nitrogen atom and 1 oxygen atom)
NO_x	Oxides of Nitrogen (any compound having nitrogen and oxygen atoms)
O_3	Ozone
P	Pressure (N/m^2)
P_a	Ambient pressure (N/m^2)
P_e	Exit pressure (N/m^2)
P_{ref}	Reference pressure (101325 N/m^2)
P_t	Stagnation pressure (N/m^2)
PE	Potential Energy (J or J/kg)
PMEP	Pumping Mean Effective Pressure (N/m^2)
Q	Heat transfer (J or J/kg)
$\dot{Q}$	Heat transfer rate (Watts or Watts/kg)
Q_R	Fuel heating value (J/kg)

Nomenclature (summary for whole course)

Symbol	Meaning (units)
R	Gas constant = $\mathfrak{R}/M$ (J/kgK)
R	Flight vehicle range (m)
r or r_c	Compression ratio $\equiv (V_c+V_d)/V_c$ (---)
r_e	Expansion ratio (---)
Re_L	Reynolds number of turbulence $\equiv u' L_I/\nu$ (---)
$\mathfrak{R}$	Universal gas constant = 8.314 J/moleK
RPM	Revolutions Per Minute (1/min)
S	Entropy (J/K)
s	Entropy per unit mass (J/kgK)
S_L	Laminar burning velocity (m/s)
S_T	Turbulent burning velocity (m/s)
ST	Specific Thrust
T	Temperature (K)
TSFC	Thrust Specific Fuel Consumption
T_{ad}	Adiabatic Flame Temperature (K)
T_t	Stagnation temperature (K)
T_w	Wall temperature
T_∞	Ambient Temperature (K)



Nomenclature (summary for whole course)

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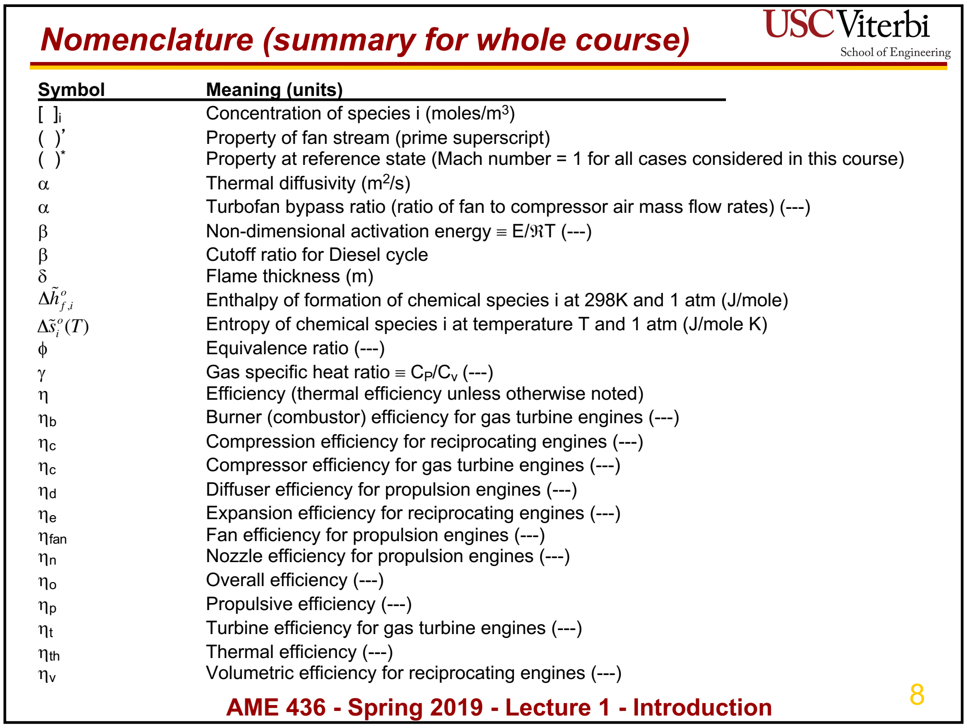
Symbol	Meaning (units)
U	Internal energy (J)
u	Internal energy per unit mass (J/kg)
u	Velocity (m/s) (most easily confused nomenclature – internal energy vs. velocity)
u_e	Exit velocity (m/s)
u_1	Flight velocity (m/s)
u’	Turbulence intensity (m/s)
UHC	Unburned hydrocarbons
V	Volume (m^3)
V_c	Clearance volume (m^3)
V_d	Displacement volume (m^3)
v	Specific volume = $1/\rho$ (m^3/kg)
W	Work transfer (J or J/kg)
$\dot{W}$	Work transfer rate (Watts or Watts/kg)
X_f	Mole fraction fuel in mixture (---)
X_i	Mole fraction of chemical species i (---)
Y_f	Mass fraction of fuel in mixture (---)
Z	Pre-exponential factor in reaction rate expression ($[moles/m^3]^{1-n}K^{-a}/s$) (n = order of reaction)
z	Elevation (m)



Nomenclature (summary for whole course)

USC Viterbi School of Engineering

Symbol	Meaning (units)
$[\ ]_i$	Concentration of species i (moles/m^3)
( )’	Property of fan stream (prime superscript)
$(\ )^*$	Property at reference state (Mach number = 1 for all cases considered in this course)
α	Thermal diffusivity (m^2/s)
α	Turbofan bypass ratio (ratio of fan to compressor air mass flow rates) (---)
β	Non-dimensional activation energy $\equiv E/\Re T$ (---)
β	Cutoff ratio for Diesel cycle
δ	Flame thickness (m)
$\Delta\tilde{h}^o_{f,i}$	Enthalpy of formation of chemical species i at 298K and 1 atm (J/mole)
$\Delta\tilde{s}^o_i(T)$	Entropy of chemical species i at temperature T and 1 atm (J/mole K)
ϕ	Equivalence ratio (---)
γ	Gas specific heat ratio $\equiv C_P/C_v$ (---)
η	Efficiency (thermal efficiency unless otherwise noted)
η_b	Burner (combustor) efficiency for gas turbine engines (---)
η_c	Compression efficiency for reciprocating engines (---)
η_c	Compressor efficiency for gas turbine engines (---)
η_d	Diffuser efficiency for propulsion engines (---)
η_e	Expansion efficiency for reciprocating engines (---)
η_{fan}	Fan efficiency for propulsion engines (---)
η_n	Nozzle efficiency for propulsion engines (---)
η_o	Overall efficiency (---)
η_p	Propulsive efficiency (---)
η_t	Turbine efficiency for gas turbine engines (---)
η_{th}	Thermal efficiency (---)
η_v	Volumetric efficiency for reciprocating engines (---)

Nomenclature (summary for whole course)

Symbol	Meaning (units)
μ	Dynamic viscosity (kg/m s)
ν	Stoichiometric coefficient (---)
ν	Kinematic viscosity $\equiv \mu/\rho$ (m^2/s)
π_i	Stagnation pressure ratio across component i (i = diffuser (d), compressor (c), burner (b), turbine (t), afterburner (ab) or nozzle (n))
π_r	$= P_{1t}/P_1$ ("recovery pressure" ratio) $= \{1 + [(\gamma-1)/2]M^2\}^{\gamma/(\gamma-1)}$ if γ = constant
ρ	Density (kg/m^3)
τ	Torque (N m)
τ_λ	$= T_{4t}/T_1$ (ratio of maximum allowable turbine inlet temperature to ambient temperature)
τ_r	$= T_{1t}/T_1$ ("recovery temperature" ratio) $= 1 + [(\gamma-1)/2]M^2$ if γ = constant
ω	Overall chemical reaction rate (1/s)

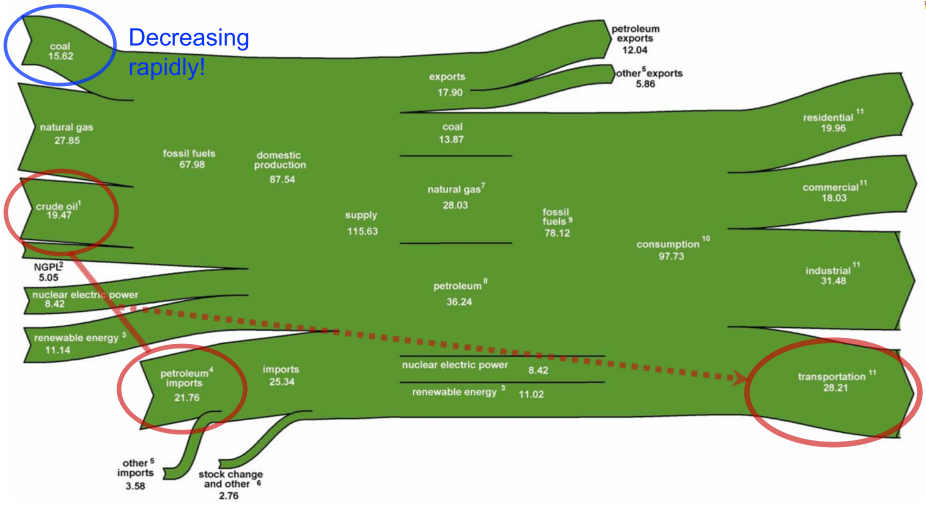
Outline of 1st lecture

- Introduction to internal combustion engines
  - World energy usage
  - Classifications of IC engines
  - Types of cycles - gas turbine, rocket, reciprocating piston gasoline / diesel
  - Why internal combustion engines? Why not something else?
  - History and evolution
  - Things you need to understand before…
- Supplemental material – not covered in lecture
  - Review of basic thermodynamics

World energy usage

- ≈ 80% of world energy production results from combustion of fossil fuels
- Energy sector accounts for ≈ 10% of US Gross Domestic Product
- Our continuing habit of burning things and our quest to find more things to burn has resulted in
  - Economic booms and busts
  - Political and military conflicts
  - Deification of oil - “the earth’s blood”
  - Global warming (or the need to deny its existence)
  - Human health issues

US energy flow, 2017, units 10^{15} BTU/yr



Each 10^{15} BTU/yr = 1 “Quad”/yr = 33.4 gigawatts

“Renewable energy”: hydroelectric, biomass, geothermal, solar, wind

http://www.eia.gov/totalenergy/data/monthly/pdf/flow/total_energy.pdf

US energy demand

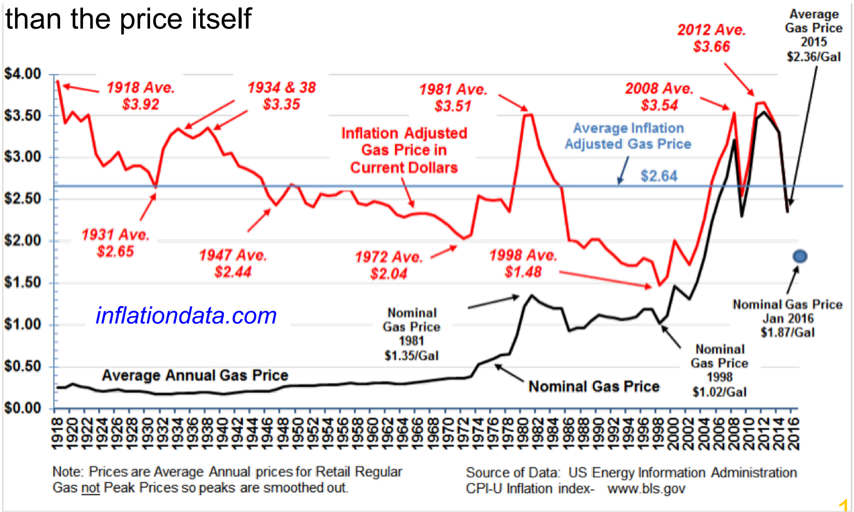
2.25 gigawatt coal power plant (Page, AZ), 34% coal-to-electricity efficiency

In 2013, Los Angeles DWP received 40% of its electricity from here and a similar plant, but plans to be coal-free by 2025 (most major CA utilities already are)

US total energy demand (not just electrical) ≈ 500 of these, running continuously 24/7

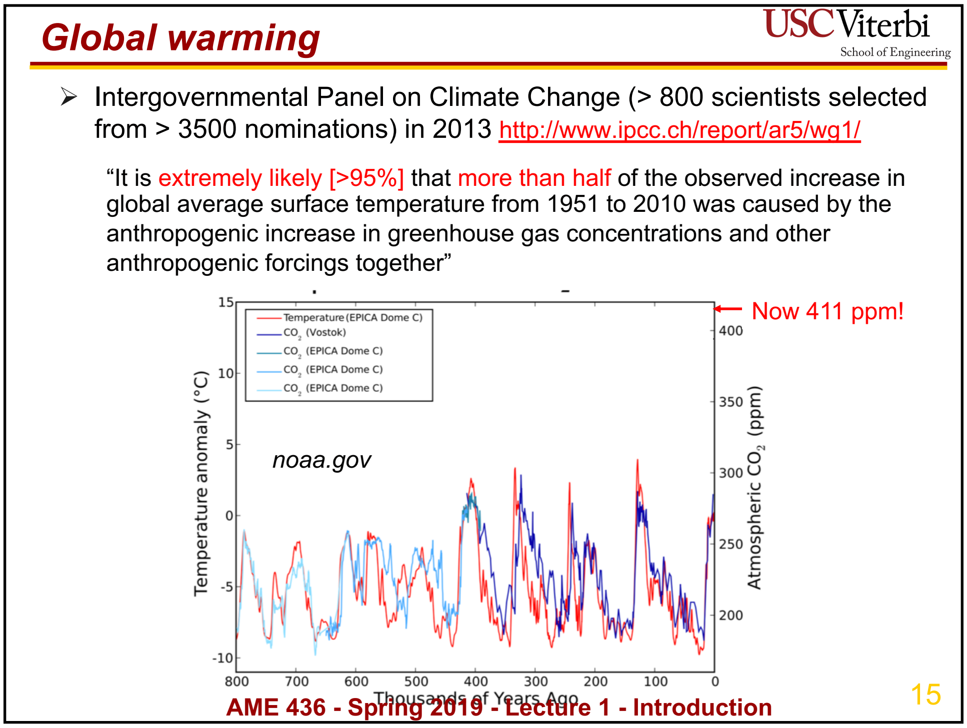
Inflation-adjusted gasoline prices

- $2.64/gal ± 50% for last 100 years
- Even during energy “crises” prices didn’t change that much
- The public is much more sensitive to the rate of change in price than the price itself



Note: Prices are Average Annual prices for Retail Regular Gas not Peak Prices so peaks are smoothed out.

Source of Data: US Energy Information Administration CPI-U Inflation index- www.bls.gov

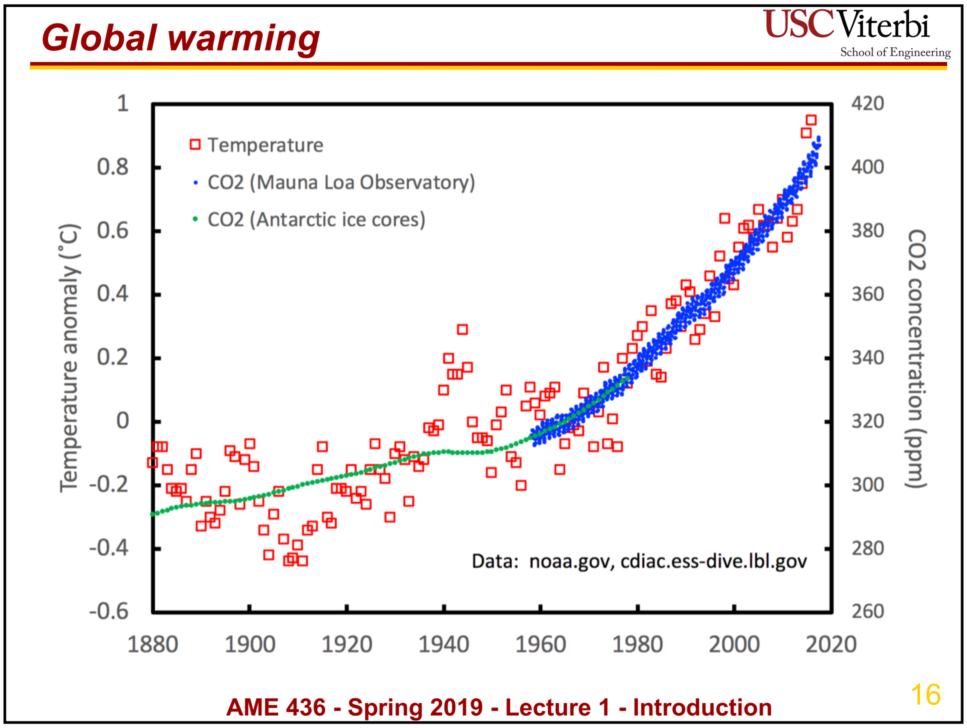


Global warming

- Intergovernmental Panel on Climate Change (> 800 scientists selected from > 3500 nominations) in 2013 http://www.ipcc.ch/report/ar5/wg1/

"It is extremely likely [>95%] that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together"

Now 411 ppm!



Global warming

Data: noaa.gov, cdiac.ess-dive.lbl.gov

Classification of ICEs

- This course focuses on the design and performance characteristics of internal combustion engines (ICEs) generally used for vehicle (car, aircraft, etc.) propulsion
- Definition of an ICE: a heat engine in which the heat source is a combustible mixture that also serves as the working fluid
- The working fluid in turn is used either to
  - Produce shaft work by pushing on a piston or turbine blade that in turn drives a rotating shaft or
  - Creates a high-momentum fluid that is used directly for propulsive force
- By this definition, ICEs include gas turbines, supersonic propulsion engines, and chemical rockets
  - This course covers only airbreathing ICEs
  - Rocket propulsion - ASTE 470

What is / is not an ICE?

IS

- Gasoline-fueled reciprocating piston engine
- Diesel-fueled reciprocating piston engine
- Gas turbine
- Rocket

IS NOT

- Steam power plant
- Solar power plant
- Nuclear power plant

ICE family tree

Internal Combustion Engines

- **Steady**
  - **Gas Turbine** Uses compressor and turbine, not piston-cylinder
    - **Turboshaft** All shaft work to drive propeller, generator, rotor (helicopter)
    - **Turbofan** Part shaft, part jet - "ducted propeller"
    - **Turbojet** All jet except for work needed to drive compressor
  - **Ramjet** No compressor or turbine Use high Mach no. ram effect for compression
  - **Rocket** Carries both fuel and oxidant Jet power only, no shaft work
    - **Solid fuel** Fuel and oxidant are premixed and put inside combustion chamber
    - **Liquid fuel** Fuel and oxidant are initially separated and pumped into combustion chamber
- **Non-steady**
  - **Premixed-charge** Fuel and air are mixed before/during compression Usually ignited with spark after compression
    - **Two-stroke** One complete thermodynamic cycle per revolution of engine
    - **Four-stroke** One complete thermodynamic cycle per two revolutions of engine
  - **Non-premixed charge** Only air is compressed, fuel is injected into cylinder after compression
    - **Two-stroke** One complete thermodynamic cycle per revolution of engine
    - **Four-stroke** One complete thermodynamic cycle per two revolutions of engine

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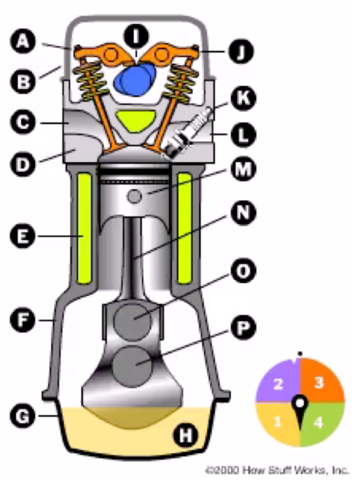
Reciprocating piston engines (gasoline/diesel)



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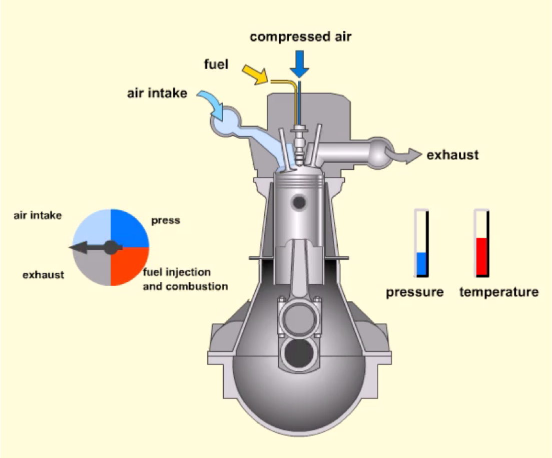
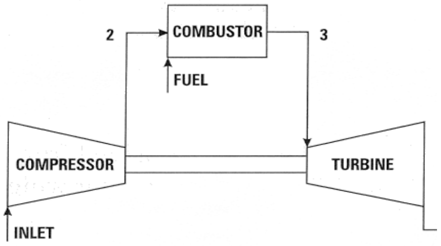
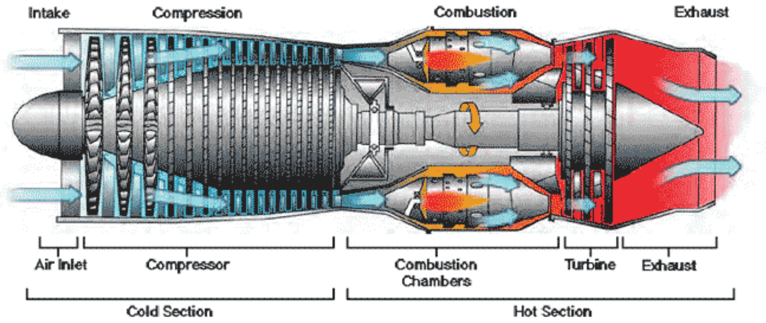


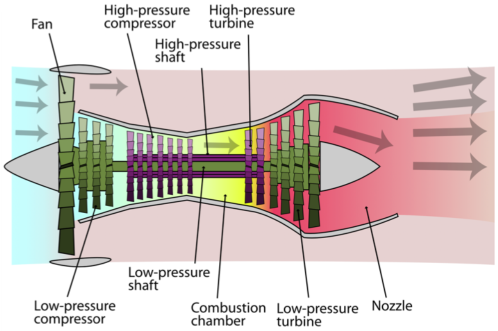
http://www.howstuffworks.com

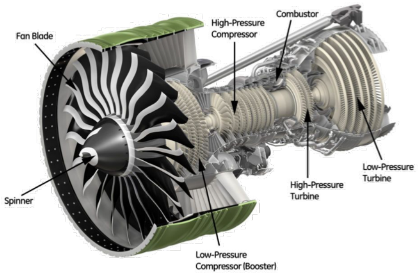
Basic gas turbine cycle





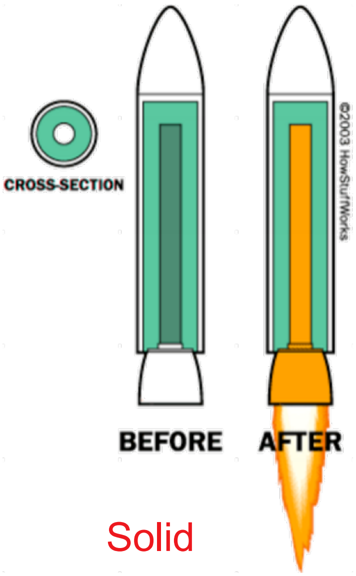
Turbofan



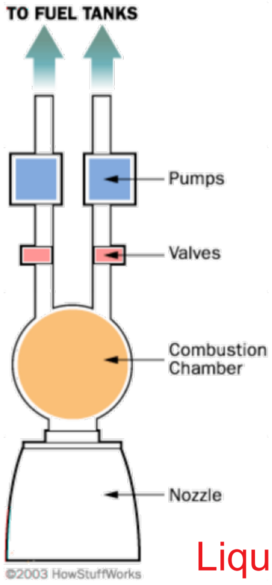


General Electric GE90

Solid / liquid rockets



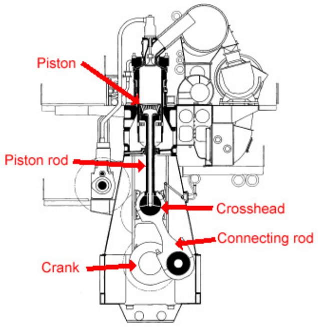
Solid

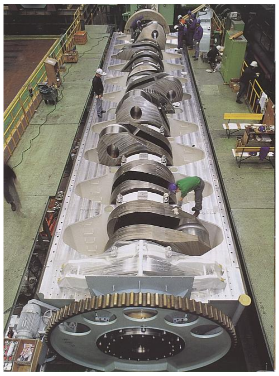


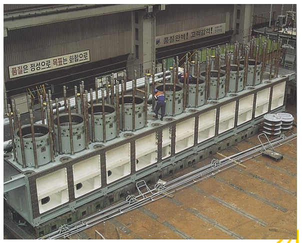
Liquid

Largest internal combustion engine

- Wartsila-Sulzer RTA96-C turbocharged two-stroke diesel, built in Finland, used in container ships
- 14 cylinder version: weight 2300 tons; length 89 feet; height 44 feet; max. power 108,920 hp @ 102 rpm; max. torque 5,608,312 ft lb @ 102 RPM
- Cylinder bore 38”, stroke 98”
- BMEP (work per cycle / volume) = 18.5 atm
- Power/weight = 0.024 hp/lb
- One of the most efficient IC engines: 51%

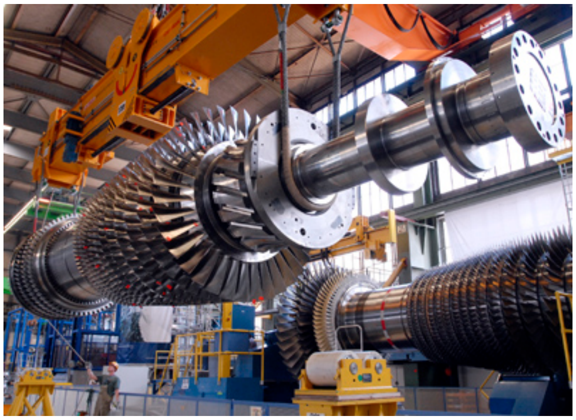






Most powerful internal combustion engine

- Wartsila-Sulzer RTA96-C is the largest IC engine, but the Space Shuttle Solid Rocket Boosters are the most powerful (≈ 42 *million* horsepower (32 hp/lb); not shaft power but kinetic energy of exhaust stream)
- Most powerful shaft-power engine: Siemens SGT5-8000H stationary gas turbine (400 MW = 536,000 HP) (0.65 hp/lb) used for electrical power generation, natural gas fuel, 40% efficiency



Smallest internal combustion engine

- Cox TeeDee 010
- Application: model airplanes
  Weight: 0.49 oz.
  Bore: 0.237" = 6.02 mm
  Stroke: 0.226" = 5.74 mm
  Displacement: 0.00997 in^3 (0.163 cm^3)
  RPM: 30,000
  Power: 3 watts
  Ignition: Glow plug
  BMEP: 0.36 atm (low!)
- Typical fuel: castor oil (10 - 20%), nitromethane (0 - 50%), balance methanol
- Decent power/weight (0.22 hp/lb) but poor performance
  - Low efficiency (< 5%)
  - Emissions & noise

Alternatives to ICEs – introduction

- What are the alternatives to ICEs for vehicle propulsion? Why are they still the exception rather than the norm?
- This discussion isn't intended to promote fossil fuel combustion over the alternatives, but shows why we currently do what we do
- If you're going to replace traditional energy, these are the limitations of the alternatives that you'll need to overcome
- Disclaimers
  - I have no current research funding or consulting arrangements from fossil fuel, automotive or green energy companies
  - I currently have research funding for both traditional (*i.e.*, combustion) and alternative (*e.g.,* fuel cell) energy conversion
  - I have no vested financial or professional interest in promoting either conventional or alternative energy
  - I have a vested interest in teaching you how to make informed design decisions regarding energy conversion devices, conventional and alternative

---

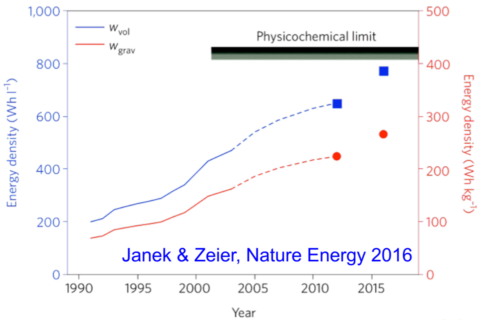
Alternative #1 - external combustion

- Examples: steam engine, Stirling cycle engine – some advantages
  - Use any fuel as the heat source
  - Use any working fluid (high γ, e.g. helium, provides better efficiency)
- Heat transfer inside typical ICE
  - Heat transfer per unit area (q/A) = k(dT/dx)
  - Turbulent mixture inside engine:
    $k \approx 100\ k_{\text{no turbulence}} \approx 2.5$ W/mK
  - $dT/dx \approx \Delta T/\Delta x \approx 1500\text{K} / 0.02$ m
  - $q/A \approx 1.9 \times 10^5$ W/m^2
- Combustion: $q/A = \rho Y_f Q_R S_T$
  $= (10\ \text{kg/m}^3) \times 0.067 \times (4.3 \times 10^7\ \text{J/kg}) \times 2$ m/s
  $= 6.0 \times 10^7$ W/m^2 - 321x higher than heat transfer!
- CONCLUSION: HEAT TRANSFER IS TOO SLOW!!!
- That's why 10 GE90 engines ≈ large (1 gigawatt) coal-fueled electric power plant

k = gas thermal conductivity, T = temperature, x = distance,
ρ = density, Y_f = fuel mass fraction, Q_R = fuel heating value,
S_T = turbulent flame speed in engine

Alternative #2 - electric vehicles (EVs)

- Generate electricity in central power plant (net efficiency $\eta \approx 35\%$), charge batteries, run electric motors ($\eta \approx 90\%$)
- Chevy Bolt Li-ion battery
  - 60 kWh (100% - 0% charge, diminishes battery life), 960 pounds = 5.0×10^5 J/kg (http://en.wikipedia.org/wiki/Chevrolet_Bolt)
  - Replacement list price $15,700
- Gasoline (& other hydrocarbons): 4.3×10^7 J/kg (11,900 W-hr/kg)
- Even at 30% efficiency (gasoline) vs. 90% (batteries), gasoline has 29 times higher energy/weight than batteries!
- 1 gallon of gasoline ≈ 175 pounds of batteries for same energy delivered to the wheels
- Also – recharging rate: 7 KW (EV, home) or 85 KW (Tesla Supercharger station) vs. 5000 KW (gasoline pump)



Janek & Zeier, Nature Energy 2016

"Zero emission" electric vehicles

Alternative #2 - electric vehicles (EVs)

- Other issues with electric vehicles
  - "Zero emissions" ? - EVs export pollution
  - MPG$_e$ = “equivalent” energy based only on electrical energy stored in the battery, not the energy required to generate that electricity
    - » 100 MPG$_e$ ≈ 35 MPG in terms of fuel burned (and CO$_2$ produced)
  - 33% of US electricity is by produced via coal at 35% efficiency – virtually no reduction in CO$_2$ emissions with EVs
  - Environmental cost of battery materials
  - Advantage: makes smaller, lighter, streamlined cars more acceptable
    Plus side: cost of electricity (Joules/$) slightly higher than gasoline but ≈ 3x higher efficiency (fuel to shaft power), thus EVs have lower “fuel” cost
- Economics of batteries
  - Bulk Li-ion batteries cost ≈ $387/kW-hr (GM supplier: $145/kW-hr)
  - Lifetime ≈ 1000 charge/discharge cycles, thus $0.39/kW-hr
  - Cost of electricity ≈ $0.134/kW-hr
  - Battery cost is ≈ 3x greater than value of all electricity it can store over its entire lifetime – Tesla Powerwall™ makes no financial sense without subsidies

Alternative #2 - electric vehicles (EVs)

- Tesla
  - Different strategy - performance car, not economy car – excels in acceleration, handling, coolness factor …
  - “Zero Emission Vehicle” credits – worth ≈ $35,000 per vehicle (LA Times, 8/23/2013, page B4)
  - Cost ≥ $81,000 with 85 kW-hr battery (1200 lb) (5.6 x 10^5 J/kg)
  - “Free” electricity at their charging stations – what is value?

$$100{,}000\text{ miles}\times\frac{\text{gallon}}{35\text{ miles}}\times\frac{\$3}{\text{gallon}}=\$8{,}570$$

  - Option (at time of vehicle purchase) to replace battery after 8 years: $12,000 – nullifies value of free recharges

Alternative #3 - Hydrogen fuel cell

USC Viterbi School of Engineering

nucellsys.com (dead link)

- NuCellSys HY-80 "Fuel cell engine" (power/wt = 0.19 hp/lb)
- ≈ 50% efficient (fuel to electricity)
- MUST use hydrogen (from where?)
- Requires > $10,000 of platinum
- Does NOT include electric drive (≈ 0.40 hp/lb thus fuel cell + motor at ≈ 90% electrical to mechanical efficiency)
- Overall system: ≈ 0.13 hp/lb at 43% efficiency (hydrogen)
- Conventional engine: ≈ 0.5 hp/lb at 30% efficiency (gasoline)
- Conclusion: fuel cell engines are only marginally more efficient, much heavier for the same power, and require hydrogen which is very difficult and potentially dangerous to store on a vehicle
- Prediction: even if we had an unlimited free source of hydrogen and a perfect way of storing it on a vehicle, *we would still burn it, not use it in a fuel cell*

Hydrogen storage

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- Hydrogen is a great fuel
  - High energy density (1.2×10^8 J/kg, ≈ 3x hydrocarbons)
  - Faster reaction rates than hydrocarbons (≈ 10 - 100x at same T)
  - Excellent electrochemical properties in fuel cells
- But how to store it???
  - Cryogenic (very cold, -424˚F) liquid, low density (14x lower than water)
  - Compressed gas: weight of tank ≈ 17x greater than weight of fuel (Toyota Murai); energy required to compress ≈ energy stored in H_2
  - Borohydride solutions
    - » $NaBH_4 + 2H_2O \rightarrow NaBO_2$ (Borax) + $3H_2$
    - » (mass solution)/(mass fuel) ≈ 9.25
  - Palladium - Pd/H = 164 by weight
  - Carbon nanotubes - many claims, few facts…
  - Long-chain hydrocarbon $(CH_2)_x$: (Mass C)/(mass H) = 6, plus C atoms add 94.1 kcal of energy release to 57.8 for H_2!
- MORAL: By far the best way to store hydrogen is to attach it to carbon atoms and make hydrocarbons, even if you're not going to use the carbon as fuel!

Alternative #4 - solar vehicle

- Arizona, high noon, mid summer: solar flux ≈ 1000 W/m^2
- Gasoline engine, 30 mi/gal, 60 mi/hr, thermal power = (60 mi/hr / 30 mi/gal) x (6 lb/gal) x (kg / 2.2 lb) x (4.3 x 10^7 J/kg) x (hr / 3600 sec) = 64 kilowatts (thermal power)
- Need ≈ 64 m^2 collector ≈ 26 ft x 26 ft - lots of air drag, what about underpasses, nighttime, bad weather, northern/southern latitudes, reserve power for acceleration, etc.?

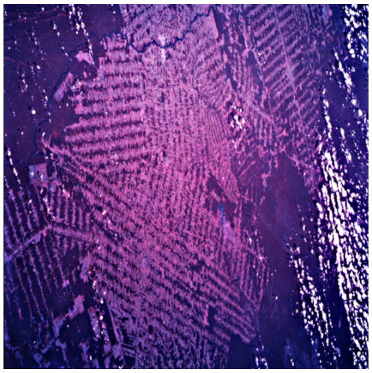
Do you want to drive one of these every day (but never at night?)

Alternative #4 - solar

- Ivanpah solar thermal electric generating station (California desert)
  - 3 towers, each 460 ft tall; land area 6 mi^2, 173,500 mirrors
  - 400 MW maximum power, 82 MW annual average in 2017 (typical coal or nuclear plant: 1,000 MW)
  - Annual natural gas usage (to keep boilers hot at night): 41 MW
  - Capital cost \$2.2 billion = \$27/watt vs. \$1/watt for natural gas power plants, \$3/watt for coal … and maintenance costs?
  - Impact on desert wildlife? (28,000 birds/yr?)
- Topaz solar photovoltaic, near Bakersfield: 145 MW avg., \$17/watt
- How to store electrical energy on a large scale for nighttime power?

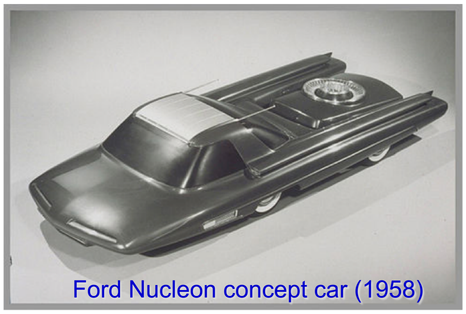
Alternative #5 - biofuels

- Essentially solar energy – “free” (?)
- Barely energy-positive; requires energy for planting, fertilizing, harvesting, fermenting, distilling
- Very land-inefficient compared to other forms of solar energy – life forms convert < 1% of sun’s energy into combustible material
- Subsidies ended in 2011, but mandate for biofuels to replace fossil petroleum continues
  - 37 billion gallons by 2022
  - ≈ 16% of by volume, 12% by energy
- Displaces other plants – not necessarily “carbon neutral”
- Uses other resources - arable land, water – that might otherwise be used to grow food or provide biodiversity (e.g. in tropical rain forests)



Alternative #6 - nuclear

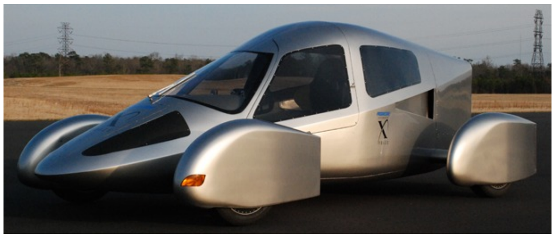
- Who are we kidding ???
- Higher energy density though
  - U_{235} fission: 8.2×10^{13} J/kg ≈ 2 million x hydrocarbons!
  - Radioactive decay much less (2.0×10^{9} J/kg for Pu-238), but still much higher than hydrocarbons



Ford Nucleon concept car (1958)

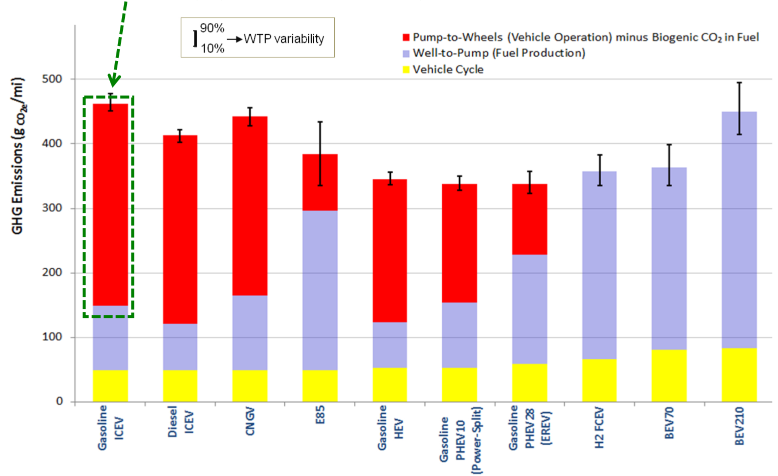
Alternative #7 - common sense

- http://www.edison2.com (no activity since 2013?)
- Won X-prize competition (https://www.xprize.org/prizes/auto) for 4-passenger vehicles (110 MPG)
- Lightweight (830 lb), aerodynamic, low rolling resistance
- Engine: 1 cylinder, 40 hp, 250 cc, turbocharged ICE
- Ethanol fuel (high octane rating, allows high compression ratio thus high efficiency)
- Rear engine placement reduces air drag due to radiator
- Beat electric vehicles despite unfair advantage in EPA MPG equivalency: 33.7 kW-hr electrical energy = 1 gal, same as raw energy content of gasoline (43 x 10^6 MJ/kg) – *doesn't account for fuel burned to create the electrical energy!*



Conclusion - alternatives to IC engines

- Total "cradle to grave" greenhouse gas (GHG) emissions ≈ same for all propulsion methods and energy sources
- Baseline 26.3 mpg gasoline ≈ 319 g CO_2/mi pump-to-wheels



http://www.hydrogen.energy.gov/pdfs/14006_cradle_to_grave_analysis.pdf

Conclusions - alternatives to IC engines

- No energy technology is without economic and environmental consequences
- Hard to beat liquid-fueled internal combustion engines for
  - Power/weight & power/volume of engine
  - Energy/weight (4.3×10^7 J/kg assuming only fuel, not air, is carried) & energy/volume of liquid hydrocarbon fuel
  - Recharging / refueling rate
  - Low materials cost
    - » ICEs: steel & aluminum
    - » Fuel cells: platinum catalyst, exotic polymer membranes, gold contacts
    - » Batteries: lead, nickel, lithium, gold contacts, …
  - Distribution & handling convenience of liquids
  - Relative safety of hydrocarbons compared to hydrogen or nuclear energy

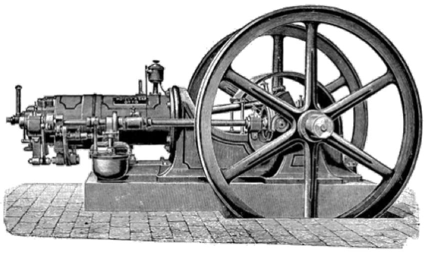
Practical alternatives…

- Conservation!
- Edison2 type vehicles
- Combined cycles
  - Use hot exhaust from ICE to heat water for conventional steam cycle
  - Can achieve > 60% efficiency
  - Not practical for vehicles - too much added volume & weight
- Natural gas (NG)
  - 3.5 cents / kW-hr (electricity 13.4, gasoline 8.3) (latest bls.gov data)
  - Somewhat cleaner than gasoline or diesel, but no environmental silver bullet
  - Low energy storage density when stored as a compressed gas at ≈ 3000 lb/in^2 - 5x lower than gasoline or diesel
  - Lowest CO_2 emissions of any fossil fuel source
  - Problem: greenhouse effect of unburned NG (escaping from production wells, filling stations, etc.) ≈ 8x that of burned NG

Practical alternatives…

- Fischer-Tropsch fuels - liquid hydrocarbons from coal or NG
  - Coal or NG + $O_2 \rightarrow CO + H_2 \rightarrow$ liquid fuel
  - Competitive with ≈ $75/barrel oil
  - Cleaner than gasoline or diesel
  - … but using coal increases greenhouse gases!
    Coal : oil : natural gas ≈ 2 : 1.5 : 1
  - Can use biomass (e.g. agricultural waste) instead of coal or natural gas as "energy feedstock"

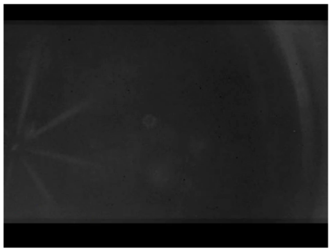
History of automotive engines

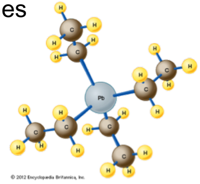


- 1859 - Oil discovered at Drake's Well, Titusville, Pennsylvania (20 barrels per day) - 40 year supply
- 1876 - Premixed-charge 4-stroke engine – Nikolaus Otto
  - 1st "practical" ICE
  - Overhead valves + crankshaft
  - 5.1 liter; 1300 lb; 160 RPM; 2 hp
  - Fuel: coal gas ($CO + H_2$)
  - Compression Ratio (CR) = 4 (knock limited), 14% efficiency (theory 38%)
  - Today CR = 9 (still knock limited), 30% efficiency (theory 55%)
  - In 143 years, the main efficiency improvement is due to better fuel

History of automotive engines

- 1897 - Nonpremixed-charge (Diesel) engine - compress air only then inject fuel - higher efficiency due to
  - Higher CR (no knocking)
  - No throttling loss - fuel/air ratio controls power
- 1901 - Spindletop Dome, east Texas - Lucas #1 gusher produces 100,000 barrels per day - ensures that “2nd Industrial Revolution” is fueled by oil, not coal or wood - 40 year supply
- 1921 - Tetraethyl lead anti-knock additive discovered at General Motors
  - Enabled higher CR (thus more power, better efficiency) in Otto-type engines
  - “End of the line” for steam & electric vehicles





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History of automotive engines

- 1938 – Oil discovered at Dammam, Saudi Arabia (40 year supply)
- 1952 - A. J. Haagen-Smit, Caltech

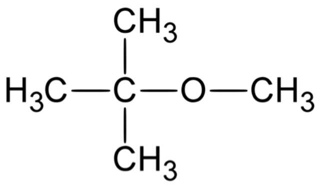
$$\underbrace{NO + UHC}_{\text{(from exhaust)}} + O_2 + \text{sunlight} \rightarrow \underset{\text{(brown)}}{NO_2} + \underset{\text{(irritating)}}{O_3}$$

(UHC = unburned hydrocarbons)

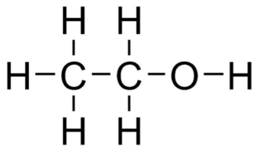
- 1960s - Emissions regulations
  - Detroit won’t believe it
  - Initial stop-gap measures - lean mixture, EGR, retard spark
  - Poor performance & fuel economy
- 1973 & 1979 – energy crises due to Middle East turmoil
  - Detroit takes a bath, Asian and European imports increase
- 1975 - Catalytic converters, unleaded fuel
  - More “aromatics” (e.g., benzene) in gasoline – restores octane # lost due to removal of TEL, but carcinogenic, soot-producing

History of automotive engines

- 1980s - Microcomputer control of engines
  - Tailor operation for best emissions, efficiency, ...
- 1990s - Reformulated gasoline (e.g., MTBE)
  - Reduced need for aromatics, cleaner (?)
  - ... but higher cost, lower miles per gallon
  - Then we found that MTBE pollutes groundwater!!!
  - Alternative “oxygenated” fuel additive - ethanol - very attractive to powerful senators from farm states in the USA



MTBE



Ethanol

History of automotive engines

- 2000’s - hybrid vehicles
  - Use small gasoline engine operating at maximum power (most efficient way to operate) or turned off if not needed
  - Use generator/batteries/motors to make/store/use surplus power from gasoline engine
  - Plug-in hybrid: half-way between conventional hybrid and electric vehicle
  - 2 benefits to car manufacturers: win-win
    - Consumers will pay a premium for hybrids
    - Helps to meet fleet-average standards for efficiency & emissions
  - Do fuel savings justify extra cost? 2014 study: only 10 of 31 hybrids tested showed a cost benefit over a 75,000 mile, 5 year ownership (http://www.vincentric.com/Home/Industry-Reports/Hybrid-Analysis-October-2014)
    - Dolly Parton: “You wouldn’t believe how much it costs to look this cheap”
    - Paul Ronney: “You wouldn’t believe how much energy some people spend to save a little fuel”
- 2010s
  - Electric-only vehicles (Tesla, Bolt, Leaf, …)
  - Small turbocharged gasoline engines (e.g. Ford Ecoboost™)

Things you need to understand before ...

…you invent the zero-emission, 100 mpg 1000 hp engine, revolutionize the automotive industry and shop for your retirement home on the French Riviera

- Room for improvement - factor of 2 in efficiency
  - Ideal Otto cycle engine with compression ratio = 9: 55%
  - Real engine: 25 - 30%
  - Differences because of
    - Throttling losses
    - Heat losses
    - Friction losses
    - Slow burning
    - Incomplete combustion is a very minor effect
- Where does work go when you drive your car? If you start at Malibu, drive to Cape Cod and stop, $\Delta KE = \Delta PE = 0$, so why did you need any work at all?
  - Majority of power is used to overcome air resistance, especially at high speeds - smaller, more aerodynamic vehicles beneficial
  - Rolling friction losses

Things you need to understand before ...

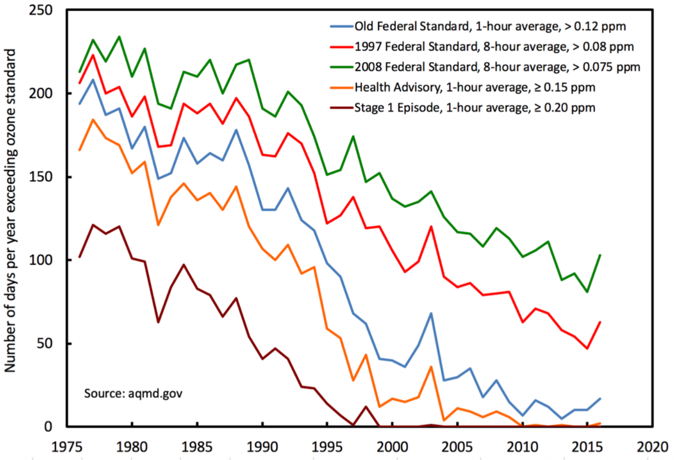
- Room for improvement - infinite in pollutants
  - Pollutants other than CO_2 are a non-equilibrium effect
    - Burn: $\text{Fuel} + O_2 + N_2 \rightarrow \underset{\text{OK}}{H_2O} + \underset{\text{OK?}}{CO_2} + \underset{\text{OK}}{N_2} + \underset{\text{Bad}}{CO} + \underset{\text{Bad}}{\text{UHC}} + \underset{\text{Bad}}{NO}$
    - Expand: CO + UHC + NO “frozen” at high levels
    - With slow expansion, no heat loss:

      $CO + \text{UHC} + NO \rightarrow H_2O + CO_2 + N_2$

      ...but how to slow the expansion and eliminate heat loss?
  - Worst problems: cold start, transients, old or out-of-tune vehicles - 90% of pollution generated by 10% of vehicles
  - Largest single source of emissions in LA air basin? Ports of Los Angeles and Long Beach
  - CO_2 and other greenhouse gases are a global not local problem

Things you need to understand before ...

- We are doing better in the SoCal Air Basin despite increasing population and miles driven
- Worst air quality (ozone): 4th St. San Bernadino; 2nd worst: Crestline, in San Bernadino Mtns. (https://www.arb.ca.gov/adam/select8/sc8start.php)



Source: aqmd.gov

Things you need to understand before ...

- Room for improvement - very little in power
  - IC engines are air processors
    - Fuel takes up little space
    - Air flow = power
    - Limitation on air flow due to
      - "Choked" flow past intake valves
      - Friction loss, mechanical strength - limits RPM
      - Slow burn
    - How to increase air flow?
      - Larger engines
      - Faster-rotating engines
      - Turbocharge / supercharge

Summary - Lecture 1

- Internal combustion engines (ICEs) use one material as both the heat source and the working fluid
- ICEs come in many sizes and many varieties, but all compress the working fluid (a gas, typically air or a fuel/air mixture), burn a fuel/air mixture, then expand the gas to produce shaft work or a high-velocity exhaust stream (ICEs work only because/when more work is extracted in the expansion process than is consumed in the compression process)
- ICEs have many advantages over other power sources, particularly power/weight of the engine and energy/mass of the fuel, and will be with us for many years to come

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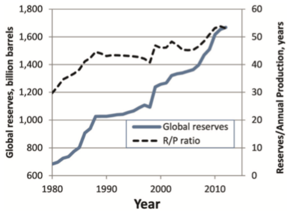
Summary - Lecture 1

- Gratuitous opinionating
  - There is no constituency for holistic, cradle-to-grave view of energy production with least total environmental impact
  - Most important problems are (in order of priority)
    - » Global warming
    - » Energy independence
    - » Environment
  - The “best” method of vehicle propulsion depends on what tax (if any) on CO_2 emissions is levied
  - The best solution to an energy/propulsion challenge is a combination of technical, economic and political factors; I can only help you with 1 out of 3 (guess which one …?)
- Ronneyisms
  - IC engines are the worst form of vehicle propulsion, except for all the other forms
  - Oil costs too much, but it’s still very cheap
  - We're 40 years away from running out of oil, and have been for the past 150 years



G. Kalghatgi, *Int. J. Engine Res.* 2014

Review of thermodynamics (1)

- Almost everything we do in this course will be analyzed with
  - 1st Law of Thermodynamics (conservation of energy) - "you can't win"
  - 2nd Law of Thermodynamics - "you can't break even"
  - Equation of state (usually ideal gas law) - "you can't even choose your poison"
  - Conservation of mass
  - Conservation of momentum

Review of thermodynamics (2)

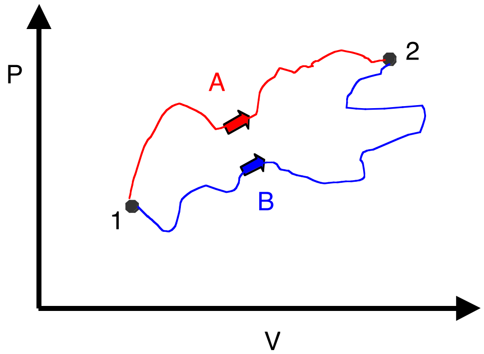
- 1st Law of Thermodynamics for a control mass, i.e. a fixed mass of material (but generally changing volume)

  $dE = \delta Q - \delta W$

  E = energy contained by the mass - a property of the mass
  Q = heat transfer to the mass
  W = work transfer to or from the mass (see below)
  d vs. δ = path-independent vs. path-dependent quantity
  - Control mass form useful for fixed mass, e.g. gas in a piston/cylinder
  - Each term has units of Joules
  - Work transfer is generally defined as positive if out of the control mass, in which case - sign applies, i.e. $dE = \delta Q - \delta W$; If work is defined as positive into system then $dE = \delta Q + \delta W$
  - Heat and work are NOT properties of the mass, they are energy transfers to/from the mass; a mass does not contain heat or work but it does contain energy (E)

Review of thermo (3) - heat & work

- Heat and work transfer depend on the path, but the internal energy of a substance at a given state doesn't depend on how you got to that state; for example, simple compressible substances exchange work with their surroundings according to $\delta W = + PdV$ (+ if work is defined as positive out of control mass)
- For example in the figure below, paths A & B have different $\int PdV$ and thus different work transfers, even though the initial state 1 and final state 2 are the same for both



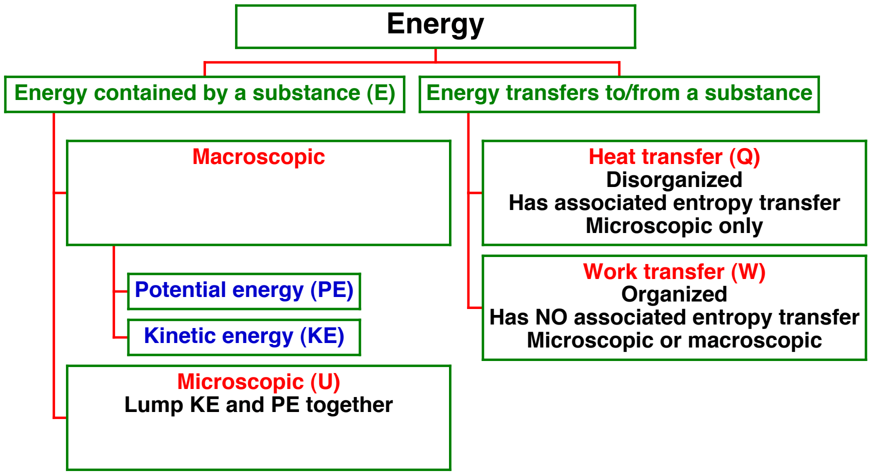
Review of thermo (4) - heat & work

- What is the difference between heat and work? Why do we need to consider them separately?
  - Heat transfer is disorganized energy transfer on the microscopic (molecular) scale and has entropy transfer associated with it
  - Work transfer is organized energy transfer which may be at either the microscopic scale or macroscopic scale and has no entropy transfer associated with it
- The energy of the substance (E) consists of
  - Macroscopic kinetic energy ($KE = 1/2\ m\mathcal{V}^2$)
  - Macroscopic potential energy ($PE = mgz$)
  - Microscopic internal energy (U) (which consists of both kinetic (thermal) and potential (chemical bonding) energy, but we lump them together since we can't see it them separately, only their effect at macroscopic scales
- If PE is due to elevation change (z) and work transfer is only PdV work, then the first law can be written as

$$(dU) + mu(du) + mg(dz) = \delta Q - P(dV)$$

u = velocity, V = volume, m = mass, g = gravity

Review of thermo (5) - types of energy



Energy

Energy contained by a substance (E)

Macroscopic

Potential energy (PE)

Kinetic energy (KE)

Microscopic (U)
Lump KE and PE together

Energy transfers to/from a substance

Heat transfer (Q)
Disorganized
Has associated entropy transfer
Microscopic only

Work transfer (W)
Organized
Has NO associated entropy transfer
Microscopic or macroscopic

Review of thermo (6) - 1st law for CV

- 1st Law of Thermodynamics for a control volume, a fixed volume in space that may have mass flowing in or out (opposite of control mass, which has fixed mass but possibly changing volume):

$$\frac{dE}{dt} = \dot{Q} - \dot{W} + \dot{m}_{in}\left(h_{in} + \frac{u_{in}^2}{2} + gz_{in}\right) - \dot{m}_{out}\left(h_{out} + \frac{u_{out}^2}{2} + gz_{out}\right)$$

  - E = energy within control volume = U + KE + PE as before
  - $\dot{Q}, \dot{W}$ = rates of heat & work transfer in or out (Watts)
  - Subscript "in" refers to conditions at inlet(s) of mass, "out" to outlet(s) of mass
  - $\dot{m}$ = mass flow rate in or out of the control volume
  - h ≡ u + Pv = enthalpy
  - Note h, u & v are lower case, i.e. per unit mass; h = H/M, u = U/M, V = v/M, etc.; upper case means total for all the mass (not per unit mass)
  - u = velocity, thus $u^2/2$ is the KE term
  - g = acceleration of gravity, z = elevation at inlet or outlet, thus gz is the PE term
- Control volume form useful for fixed volume device, e.g. gas turbine
- Most commonly written as a rate equation (as above)

Review of thermo (7) - 1st law for CV

- Note that the Control Volume (CV) form of the 1st Law looks almost the same as the Control Mass (CM) form with the addition of $\dot{m}$(h + $u^2/2$ + gz) terms that represent the flux of energy in/out of the CV that is carried with the mass flowing in/out of the CV
- The only difference between the CV and CM forms that isn't "obvious" is the replacement of u (internal energy) with h = u + Pv
- Where did the extra Pv terms come from? The flow work needed to push mass into the CV or that you get back when mass leaves the CV

Review of thermo (8) - steady flow

- If the system is steady then by definition
  - d[ ]/dt = 0 for all [properties], i.e. E_{CV}, M_{CV}, h, v, z
  - All fluxes, i.e. $\dot{m}, \dot{Q}, \dot{W}$ are constant (not necessarily zero)
  - Sum of mass flows in = sum of all mass flows out (or $\dot{m}_{in} = \dot{m}_{out}$ for a single-inlet, single-outlet system) (if we didn't have this condition then the mass of the system, which is a property of the system, would not be constant)
  - In this case (steady-state, steady flow) the 1st Law for a CV is

$$\boxed{0 = \dot{Q} - \dot{W} + \dot{m}\left[(h_{in} - h_{out}) + \left(\frac{u_{in}^2}{2} - \frac{u_{out}^2}{2}\right) + (gz_{in} - gz_{out})\right]}$$

Review of thermo (9) - conservation of mass

- For a control mass
  m = mass of control mass = constant (wasn't that easy?)
- For a control volume

$$\boxed{\frac{dm_{CV}}{dt} = \sum_{\text{all inlets}} \dot{m}_i - \sum_{\text{all outlets}} \dot{m}_j}$$

(what accumulates = what goes in - what goes out)

Review of thermodynamics (10) - 2nd law

- The 2nd Law of Thermdynamics states
  The entropy (S) of an isolated system always increases or remains the same
- By combining
  - 2nd law
  - 1st Law
  - State postulate - for a system of fixed chemical composition, 2 independent properties completely specify the state of the system
  - The principle that entropy is a property of the system, so is additive

"it can be shown" that

Tds = du + Pdv

Tds = dh - vdP

These are called the Gibbs equations, which relate entropy to other thermodynamic properties (e.g. u, P, v, h, T)

Review of thermodynamics (11) - 2nd law

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- From the Gibbs equations, “it can be shown” for a control mass

$$\boxed{dS \geq \frac{\delta Q}{T}}$$

= sign applies for a reversible (idealized; best possible) process

> applies if irreversible (reality)

T is the temperature on the control mass at the location where the heat is transferred to/from the CM

- And for a control volume

$$\boxed{\frac{dS_{CV}}{dt} + \dot{m}_{in}s_{in} - \dot{m}_{out}s_{out} \geq \frac{\dot{Q}}{T}}$$

S_{CV} is the entropy of the control volume; if steady, $dS_{CV}/dt = 0$

- These equations are the primary way we apply the 2nd law to the energy conversion systems discussed in this class
- Work doesn’t appear anywhere near the 2nd law - why? Because there is NO entropy transfer associated with work transfer, whereas there IS entropy transfer associated with heat transfer

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Review of thermo (12) - equations of state

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- We’ll only consider 2 equations of state in this course
  - Ideal gas - $P = \rho RT$ (P = pressure, $\rho = 1/v$ = density, T = temperature (absolute), R = gas constant = $\mathfrak{R}/\mathcal{M}_{mix}$, $\mathfrak{R}$ = universal gas constant (8.314 J/mole-K), $\mathcal{M}_{mix}$ = molecular weight of gas mixture)
  - Incompressible fluid - ρ = constant
- Definition of specific heats (any substance)

$$C_P \equiv \left(\frac{\partial h}{\partial T}\right)_P; C_V \equiv \left(\frac{\partial u}{\partial T}\right)_V; \gamma \equiv \frac{C_P}{C_V}$$

- For ideal gases - h = h(T) and u = u(T) only (h and u depend only on temperature, not pressure, volume, etc.), thus for ideal gases

$$C_P = \frac{dh}{dT}; C_V = \frac{du}{dT}; h = u + Pv = u + RT; \frac{dh}{dT} = \frac{du}{dT} + R \Rightarrow \boxed{C_P = C_V + R}$$

- From $dh = C_P dT$, $du = C_V dT$, the Gibbs equations and $P = \rho RT$ we can show that (again for an ideal gas only)

$$\boxed{S_2 - S_1 = C_P \ln\left(\frac{T_2}{T_1}\right) - R\ln\left(\frac{P_2}{P_1}\right) = C_V \ln\left(\frac{T_2}{T_1}\right) + R\ln\left(\frac{V_2}{V_1}\right) = C_V \ln\left(\frac{P_2}{P_1}\right) + C_P \ln\left(\frac{V_2}{V_1}\right)}$$

Review of thermo (13) - isentropic relations

- Recall from the 2nd Law, $dS \geq \delta Q/T$
- If a process is reversible $dS = \delta Q/T$, and if furthermore the process is adiabatic $\delta Q = 0$ thus $dS = 0$ or $S_2 - S_1 = 0$ (isentropic process) then the previous relations for $S_2 - S_1$ can be written as

$$\boxed{\left(\frac{T_2}{T_1}\right) = \left(\frac{P_2}{P_1}\right)^{\gamma-1/\gamma} ; \left(\frac{T_2}{T_1}\right) = \left(\frac{v_1}{v_2}\right)^{\gamma-1} ; \left(\frac{P_2}{P_1}\right) = \left(\frac{v_1}{v_2}\right)^{\gamma}}$$

Isentropic processes are our favorite model for compression and expansion in engines

- But remember these relations are valid only for
  - Ideal gas
  - Constant specific heats (C_P, C_V) (note that since for an ideal gas $C_P = C_v + R$ and R is a constant, if any of C_P, C_v and $\gamma = C_P/C_v$ are constant then the other two must be constant also)
  - Reversible adiabatic (thus isentropic) process

(Still very useful despite all these restrictions…)