Internal Combustion Engines: The Worst Form of Vehicle Propulsion - Except for All the Other Forms

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Download this presentation: http://ronney.usc.edu/WhyICEngines-expanded.pptx
Introductions
  Personal
  To this subject
Some remarks about US and global energy / environmental trends
Definition of Internal Combustion Engines (ICEs)
Types of ICEs
History and evolution of ICEs
Things you need to know before…
What are the alternatives?
Practical perspective

(Optional) engine lab tour – 9:15 am tomorrow (Friday)
morning, meet at OHE elevators, lab is in OHE basement
Introduction

- Hydrocarbon-fueled ICEs are the power plant of choice for vehicles in the power range from 5 Watts to 100,000,000 Watts, and have been for over 100 years.
- There is an unlimited amount of inaccurate, misleading and/or dogmatic information about ICEs.
- This seminar's messages:
  - Why ICEs are so ubiquitous
  - Why it will be so difficult to replace them with another technology
  - What you will have to do if you want to replace them
- Ask questions, challenge me and each other – discussion is more important than lecture
Our current energy economy, based primarily on fossil fuel usage, evolved because it was the cheapest system. Is it possible that it's also the most environmentally responsible (or “least environmentally irresponsible”) system?
US energy usage

- > 80% of world energy production results from combustion of fossil fuels
- Energy sector accounts for 9% 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
Global warming


“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”

Currently 399 ppm!
US energy flow, 2011, units $10^{15}$ BTU/yr

Each $10^{15}$ BTU/yr = 33.4 gigawatts

http://www.eia.gov/totalenergy/data/annual/diagram1.cfm
US energy demand

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

US total energy demand (not just electrical) ≈ 490 of these, running continuously 24/7
Inflation-adjusted gasoline prices

- $1.50 - $3.00/gal 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
Classification of ICEs

- 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.
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

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

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
Largest internal combustion engine

- Wartsila-Sulzer RTA96-C turbocharged two-stroke diesel, built in Finland, used in container ships
- 14 cyl. 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
- Power/weight = 0.024 hp/lb
- Also one of the most efficient IC engines: 51%
Most powerful internal combustion engine

- Wartsila-Sulzer RTA96-C is largest IC engine, but Space Shuttle Solid Rocket Boosters are 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 (340 MW = 456,000 HP) (0.52 hp/lb) used for electrical power generation
Smallest internal combustion engine

- Cox Tee Dee 010
  - Application: model airplanes
  - Weight: 0.49 oz.
  - Displacement: 0.00997 in$^3$ (0.163 cm$^3$)
  - RPM: 30,000
  - Power: 5 watts
  - Ignition: Glow plug

- Typical fuel: castor oil (10 - 20%), nitromethane (0 - 50%), balance methanol

- Good power/weight (0.22 hp/lb) but poor performance
  - Low efficiency (< 3%)
  - Emissions & noise unacceptable for many applications
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 + H₂)
  - Compression Ratio (CR) = 4 (knock limited), 14% efficiency (theory 38%)

\[
\text{Efficiency} = \frac{\text{What you get}}{\text{What you pay for}} = \frac{\text{Work output}}{\text{Fuel energy input}}
\]

- Today CR = 9 (still knock limited), 30% efficiency (theory 55%)
- In 138 years, the main efficiency improvement is due to better fuel
Engine knock - movies

No knock

Knock

Videos courtesy Prof. Yuji Ikeda, Kobe University
History of automotive engines

- 1897 - Nonpremixed-charge (Diesel) engine - compress air only then add fuel - higher efficiency due to
  - Higher CR (no knocking)
  - No throttling loss - use fuel/air ratio to control power

- 1901 - Spindletop Dome, east Texas - Lucas #1 gusher produces 100,000 barrels per day - ensures that “2nd Industrial Revolution” will be 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
History of automotive engines

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

\[
\text{NO} + \text{UHC} + \text{O}_2 + \text{sunlight} \rightarrow \text{NO}_2 + \text{O}_3
\]

(from exhaust) (brown) (irritating)

(UHC = unburned hydrocarbons)

- 1960s - Emissions regulations
  - Detroit won't believe it
  - Initial stop-gap measures - lean mixture, exhaust gas recirculation (EGR), retard spark
  - Poor performance & fuel economy
- 1973 & 1979 - The 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 - high octane but
carcinogenic, soot-producing

1980s - Microcomputer control of engines
   - Tailor operation for best emissions, efficiency, ...

1990s - Reformulated gasoline
   - 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
History of automotive engines

2000s - 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? Consumer Reports study: only 1 of 7 hybrids tested showed a cost benefit over a 5 year ownership if tax incentives were removed
  » Dolly Parton: “It costs a lot of money to look this cheap”
  » PDR: “You have to consume a lot of energy to save a little fuel”

2010 and beyond

- Electric vehicles?
- 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 less than 2 in efficiency
  - Ideal Otto cycle engine with compression ratio = 9: 55%
  - Real engine: ≤ 30%
  - Differences because of
    » Throttling losses
    » Heat losses
    » Friction losses
    » Slow burning
    » Incomplete combustion is a very minor effect

- Majority of power is used to overcome air resistance - smaller, more aerodynamic vehicles beneficial
Things you need to understand before ...

- Room for improvement - infinite in pollutants
  - Pollutants are a non-equilibrium effect
    - Burn: Fuel + O₂ + N₂ → H₂O + CO₂ + N₂ + CO + UHC + NO
      - OK OK(?) OK Bad Bad Bad
    - Expand: CO + UHC + NO “frozen” at high levels
  - With slow expansion, no heat loss:
    CO + UHC + NO → H₂O + CO₂ + N₂
    ...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
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
Alternative #1 - external combustion

- Examples: steam engine, Stirling cycle engine
  - Use any fuel as the heat source
  - Use any working fluid (high $\gamma$, e.g. helium, provides better efficiency)
- Heat transfer rate
  - 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
  - $dT/dx \approx \Delta T/\Delta x \approx 1500$K / 0.02 m
  - $q/A \approx 187,500$ W/m$^2$
- Combustion: $q/A = \rho Y_f Q_R S_T = (10$ kg/m$^3$) x 0.067 x (4.5 x 10$^7$ J/kg) x 2 m/s = 60,300,000 W/m$^2$ - 321x higher!
- CONCLUSION: HEAT TRANSFER IS TOO SLOW!!!
- That's why 10 large gas turbine engines $\approx$ large (1 gigawatt) coal-fueled electric power plant

$k =$ gas thermal conductivity, $T =$ temperature, $x =$ distance,
$\rho =$ 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 (efficiency $\eta \approx 35\%$), charge batteries, run electric motors ($\eta \approx 90\%$)
- Chevy Volt Li-ion battery - 10.4 kW-hr (90% to 25% of capacity, restricted by software), 435 pounds = $1.9 \times 10^5$ J/kg ([http://en.wikipedia.org/wiki/Chevrolet_Volt](http://en.wikipedia.org/wiki/Chevrolet_Volt))
- Gasoline (and other hydrocarbons): $4.3 \times 10^7$ J/kg
- Even at 30% efficiency (gasoline) vs. 90% (batteries), gasoline has 76 times higher energy/weight than batteries!
- 1 gallon of gasoline $\approx 466$ pounds of batteries for same energy delivered to the wheels
- Also – recharging rate: 10 KW (EV, home) or 85 KW (Tesla Supercharger station) vs. 5000 KW (gasoline pump)
“Zero emission” electric vehicles
Alternative #2 - electric vehicles (EVs)

- Other issues with electric vehicles
  - "Zero emissions" ??? - EVs export pollution
  - \( \text{MPG}_e = \text{“equivalent” energy based only on electricity stored in the battery, not the energy required to generate that electricity} \)
    - \( 100 \text{ MPG}_e \approx 35 \text{ MPG} \) in terms of fuel burned (and \( \text{CO}_2 \) produced)
  - 50% of US electricity is by produced via coal at 35% efficiency – virtually no reduction in \( \text{CO}_2 \) emissions with EVs
  - Environmental cost of battery materials
  - Possible advantage: makes smaller, lighter, more streamlined cars acceptable to consumers
  - Plus side: cost of electricity (Joules/$) \approx \) same as gasoline but \( \approx 3x \) higher efficiency (fuel to shaft power), thus EVs have lower “fuel” cost

- Economics of batteries
  - Cost of Li-ion batteries in bulk \( \approx $500/\text{kW-hr} \)
  - Lifetime 1000 charge/discharge cycles, thus \( \$0.50/\text{kW-hr} \)
  - Cost of electricity \( \approx $0.10/\text{kW-hr} \)
  - The battery cost is 5 times more than the value of all of the electricity it will 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, …
  - “Zero Emission Vehicle” credits – worth $\approx 35,000$ per vehicle (LA Times, 8/23/2013, page B4)
  - Cost $\geq 81,000$ with 85 kW-hr battery (1200 lb) $(5.6 \times 10^5 \text{ J/kg})$ (???)
  - “Free” electricity at their charging stations – what is value?
    
    $$\text{100,000 miles} \times \frac{\text{gallon}}{35 \text{ miles}} \times \frac{\$4}{\text{gallon}} = \$11,400$$

- Option to replace battery after 8 years: $12,000 – wipes out free recharges
Alternative #3 - Hydrogen fuel cell

- NuCellSys HY-80 “Fuel cell engine” (power/wt = 0.19 hp/lb)
- 48% efficient (fuel to electricity)
- MUST use hydrogen (from where? \( \text{H}_2 \) is an energy carrier, not a fuel)
- Requires > $10,000 of platinum
- Does NOT include electric drive system
- Overall system: 0.13 hp/lb at 43% efficiency
- Conventional engine: \( \approx 0.5 \text{ hp/lb at 30\% efficiency} \)
- Conclusion: fuel cell engines only marginally more efficient, much heavier & require hydrogen vs. gasoline
- 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 is a great fuel
- High energy density (1.2 x 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 ≈ 15x greater than weight of fuel
- Borohydride solutions
  » NaBH_4 + 2H_2O → 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 vehicles

- Arizona, high noon, mid summer: solar flux ≈ 1000 W/m²
- Gasoline engine, thermal power = \((60 \text{ mi/hr} / 30 \text{ mi/gal}) \times (6 \text{ lb/gal}) \times (\text{kg} / 2.2 \text{ lb}) \times (4.3 \times 10^7 \text{ J/kg}) \times (\text{hr} / 3600 \text{ sec})\) = 65 kilowatts
- Need ≈ 65 m² collector ≈ 26 ft x 26 ft - lots of air drag, what about underpasses, nighttime, bad weather, northern/southern latitudes, etc.?

Do you want to drive one of these every day (but never at night?)
Alternative #4 – solar vehicles

- Ivanpah solar thermal electric generating station (California desert, 250 km from Los Angeles)
- 3 towers, each 460 ft tall; land area 6 mi², 17,000 mirrors
- 400 MW maximum power, 123 MW annual average (small compared to typical coal or nuclear plant, 1,000 MW)
- Capital cost $2.2 billion = $18/watt vs. $1/watt for conventional natural gas power plants, $3/watt for coal
- Impact on desert wildlife? (28,000 birds/yr?)
- Maintenance costs?
Alternative #5 - biofuels

- Essentially solar energy – “free” (?)
- Barely energy-positive: requires energy for planting, fertilizing, harvesting, fermenting, distilling
- Very land-inefficient – life forms convert < 1% of solar energy into combustible material
- Currently 3 subsidies on US bio-ethanol:
  - 45¢/gal (≈ 67¢/gal gasoline) tax credit to refineries
  - 54¢/gal tariff on sugar-based ethanol imports
  - Requirement for 10% ethanol in gasoline
- 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 ???
- High energy density though
  - $^{235}\text{U}$ fission: $8.2 \times 10^{13} \text{ J/kg} \approx 2 \text{ million x hydrocarbons!}$
  - Radioactive decay much less ($2.0 \times 10^{9} \text{ J/kg for Pu-238}$), but still much higher than hydrocarbons

Ford Nucleon concept car (1958)
Alternative #7 – common sense

- [http://www.edison2.com](http://www.edison2.com)
- Won X-prize competition for 4-passenger vehicles (110 MPG)
- Low weight (830 lb), aerodynamic, very low rolling resistance
- Engine: 1 cylinder, 40 hp, 250 cc, turbocharged ICE
- Ethanol fuel (high octane, allows high CR thus high efficiency)
- Rear engine placement reduces air drag due to radiator
- Beat electric vehicles despite unfair advantage in US EPA MPG equivalency: 33.7 kW-hr electrical energy = 1 gal, same as raw energy content of gasoline – doesn’t account for fuel burned to create electrical energy!
Conclusion - alternatives to IC engines

- Total “cradle to grave” CO₂ emissions ≈ same for all propulsion methods and energy sources!

Summary of advantages of ICEs

- Moral - hard to beat liquid-fueled internal combustion engines for
  - Power/weight & power/volume of engine
  - Energy/weight \(4.3 \times 10^7 \text{ J/kg}\) & energy/volume of liquid hydrocarbon fuel
  - Distribution & handling convenience of liquids
  - Relative safety of hydrocarbons compared to hydrogen or nuclear energy
  - Cost of materials (steel & aluminum)
Practical alternatives…

- Conservation!
- Combined cycles: use hot exhaust from ICE to heat water for conventional steam cycle - can achieve > 60% efficiency but not practical for vehicles - too much added volume & weight
- Natural gas (NG) – mostly methane (CH$_4$)
  - 4x cheaper than electricity, 2x cheaper than gasoline or diesel for same energy
  - Somewhat cleaner than gasoline or diesel, but no environmental silver bullet
  - Low energy storage density - 4x lower than gasoline or diesel
  - Lowest CO$_2$ emissions of any fossil fuel source
  - Problem: greenhouse effect of unburned NG (from production wells, filling stations, etc.) ≈ 8x that of burned NG
Practical alternatives... discussion points

- Fischer-Tropsch fuels - liquid hydrocarbons from coal or natural gas
  - Coal or NG + O₂ → CO + H₂ → 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
  - What about using biomass (e.g. agricultural waste) instead of coal or natural gas as “energy feedstock”

- But really, there is no way to decide what the next step is until it is decided whether there will be a tax on CO₂ (and maybe other greenhouse gas) emissions

- Personal opinion: most important problems are (in order of priority)
  - Global warming
  - Energy independence
  - Environment
Conclusions

- 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
- There is no constituency for holistic, cradle-to-grave view of energy production with least total environmental impact
Some backup slides in case anyone asks
Power and torque

- Engine performance is specified in both in terms of power and engine torque - which is more important?
  - Wheel torque = engine torque x gear ratio tells you whether you can climb the hill
  - Gear ratio in transmission typically 3:1 or 4:1 in 1st gear, 1:1 in highest gear; gear ratio in differential typically 3:1
    - Ratio of engine revolutions to wheel revolutions varies from 12:1 in lowest gear to 3:1 in highest gear
  - Power tells you how fast you can climb the hill
  - Torque can be increased by transmission (e.g. 2:1 gear ratio ideally multiplies torque by 2)

\[
P \text{ (in horsepower)} = \frac{N \text{ (revolutions per minute, RPM)} \times \text{Torque (in foot pounds)}}{5252}
\]

- Power can't be increased by transmission; in fact because of friction and other losses, power will decrease in transmission
- Power tells how fast you can accelerate or how fast you can climb a hill, but power to torque ratio ~ N tells you what gear ratios you'll need to do the job
**4-stroke premixed-charge piston engine**

- Most common type of IC engine
- Simple, easy to manufacture, inexpensive materials
- Good power/weight ratio
- Excellent flexibility - works reasonably well over a wide range of engine speeds and loads
- Rapid response to changing speed/load demand
- “Acceptable” emissions
- Weaknesses
  - Fuel economy (compared to Diesel, due lower compression ratio & throttling losses at part-load)
  - Power/weight (compared to gas turbine)
4-stroke premixed-charge piston engine

Animation: http://static.howstuffworks.com/flash/engine.swf

Note: ideally combustion occurs in zero time when piston is at the top of its travel between the compression and expansion strokes
Throttling

- When you need less than the maximum torque available from a premixed-charge engine (which is most of the time), a throttle is used to control torque & power.
- Throttling adjusts torque output by reducing intake density through decrease in pressure.
- Throttling loss significant at light loads (see next page).
- Control of fuel/air ratio can adjust torque, but cannot provide sufficient range of control - misfire problems with lean mixtures.
- Diesel - nonpremixed-charge - use fuel/air ratio control - no misfire limit - no throttling needed.
- Throttling loss increases from zero at wide-open throttle (WOT) to about half of all fuel usage at idle (other half is friction loss)
- At typical highway cruise condition (≈ 1/3 of torque at WOT), about 15% loss due to throttling
- Throttling isn't always bad, when you take your foot off the gas pedal & shift to a lower gear to reduce vehicle speed, you're using throttling loss (negative torque) and high N to maximize negative power
Another way to reduce throttling losses: close off some cylinders when low power demand

- Cadillac had a 4-6-8 engine in the 1981 but it was a mechanical disaster
- GM uses a 4-8 “Active fuel management” (previously called “Displacement On Demand”) engine
- Mercedes has had 4-8 “Cylinder deactivation” engines for European markets since 1998:
  [http://www.answers.com/topic/active%20cylinder%20control](http://www.answers.com/topic/active%20cylinder%20control)

Many auto magazines suggest this will cut fuel usage in half, as though engines use fuel based only on displacement, not RPM (N) or intake manifold pressure - more realistic articles report 8 - 10% improvement in efficiency
2-stroke premixed-charge engine

- Most designs have fuel-air mixture flowing first INTO CRANKCASE (?)
- Fuel-air mixture must contain lubricating oil
- On down-stroke of piston
  - Exhaust ports are exposed & exhaust gas flows out, crankcase is pressurized
  - Reed valve prevents fuel-air mixture from flowing back out intake manifold
  - Intake ports are exposed, fresh fuel-air mixture flows into intake ports
- On up-stroke of piston
  - Intake & exhaust ports are covered
  - Fuel-air mixture is compressed in cylinder
  - Spark & combustion occurs near top of piston travel
  - Work output occurs during 1st half of down-stroke

Animation: [http://static.howstuffworks.com/flash/two-stroke.swf](http://static.howstuffworks.com/flash/two-stroke.swf)
2-stroke premixed-charge engine

- 2-strokes gives ≈ 2x as much power since only 1 crankshaft revolution needed for 1 complete cycle (vs. 2 revolutions for 4-strokes)
- Since intake & exhaust ports are open at same time, some fuel-air mixture flows directly out exhaust & some exhaust gas gets mixed with fresh gas
- Since oil must be mixed with fuel, oil gets burned
- As a result of these factors, thermal efficiency is lower, emissions are higher, and performance is near-optimal for a narrower range of engine speeds compared to 4-strokes
- Use primarily for small vehicles, leaf blowers, RC aircraft, etc. where power/weight is the overriding concern
Rotary or Wankel engine

- Only commercially viable engine design invented after 1900
- Uses non-cylindrical combustion chamber
- Advantages
  - Provides one complete cycle per engine revolution without “short circuit” flow of 2-strokes (but still need some oil injected at the rotor apexes)
  - Simpler, fewer moving parts, higher RPM possible
  - Very fuel-flexible - can incorporate catalyst in combustion chamber since fresh gas is moved into chamber rather than being continually exposed to it (as in piston engine) - same design can use gasoline, Diesel, methanol, etc.
- Disadvantages
  - Very difficult to seal BOTH vertices and flat sides of rotor!
  - Seal longevity a problem also
  - Large surface area to volume ratio means more heat losses
Rotary or Wankel engine

Source: http://auto.howstuffworks.com/rotary-engine4.htm

Animations:
http://static.howstuffworks.com/flash/rotary-engine-animation.swf
http://static.howstuffworks.com/flash/rotary-engine-exploded.swf
4-stroke Diesel engine

- Conceptually similar to 4-stroke gasoline, but only air is compressed (not fuel-air mixture) and fuel is injected into combustion chamber after air is compressed.

- Key advantages
  - Higher compression ratio possible because no knock (only air is compressed)
  - No throttling losses since always operated at atmospheric intake pressure

http://static.howstuffworks.com/flash/diesel2.swf
Premixed vs. non-premixed charge engines

Premixed charge (gasoline)
- Spark plug
- Flame front
- Fuel + air mixture

Non-premixed charge (Diesel)
- Fuel injector
- Fuel spray flame
- Air only
2-stroke Diesel engine

- Used in large engines, e.g. locomotives
- More differences between 2-stroke gasoline vs. diesel engines than 4-stroke gasoline vs. diesel
  - Air comes in directly through intake ports, not via crankcase
  - **Must** be turbocharged or supercharged to provide pressure to force air into cylinder
  - No oil mixed with air - crankcase has lubrication like 4-stroke
  - Exhaust valves rather than ports - not necessary to have intake & exhaust paths open at same time
  - Because only air, not fuel/air mixture enters through intake ports, “short circuit” of intake gas out to exhaust is not a problem
  - Because of the previous 3 points, 2-stroke diesels have far fewer environmental problems than 2-stroke gasoline engines
Why can't gasoline engines use this concept? They can in principle but fuel must be injected & fuel+air **fully mixed** after the intake ports are covered but before spark is fired.

Also, difficult to control ratio of fuel/air/exhaust residual precisely since intake & exhaust paths are open at same time - ratio of fuel to (air + exhaust) critical to premixed-charge engine performance.

Startup, variable RPM performance problematic.

Some companies have tried to make 2-stroke premixed-charge engines operating this way, e.g. [http://www.orbeng.com.au/](http://www.orbeng.com.au/), but these engines have found only limited application.
Comparison of GM truck engines - gasoline vs. Diesel

- Recall Power (hp) = Torque (ft lb) x N (rev/min) \( \div \) 5252
- Gasoline: Torque \( \approx \) constant from 1000 to 6000 RPM; power \( \sim \) N
- Turbo Diesel: Torque sharply peaked; much narrower range of usable N (1000 - 3000 RPM) (\( P_{\text{intake}} \) not reported on website but maximum \( \approx \) 3 atm from other data)
- Smaller, non-turbocharged gasoline engine produces almost as much power as turbo Diesel, largely due to higher N

2006 GM Northstar 4.6 Liter V8 (LD8); 
\( r = 10.5 \); variable valve timing

2006 GM Duramax 6.6 liter V8 
turbocharged Diesel (LBZ); \( r = 16.8 \)
Why do we throttle in a premixed charge engine despite the throttling losses it causes?
- Because we have to reduce power & torque when we don't want the full output of the engine (which is most of the time in LA traffic, or even on the open road)

Why don't we have to throttle in a nonpremixed charge engine?
- Because we use control of the fuel to air ratio (i.e. to reduce power & torque, we reduce the fuel for the (fixed) air mass)

Why don't we do that for the premixed charge engine and avoid throttling losses?
- Because if we try to burn lean in the premixed-charge engine, when the equivalence ratio ($\phi$) is reduced below about 0.7, the mixture misfires and may stop altogether

Why isn't that a problem for the nonpremixed charge engine?
- Nonpremixed-charge engines are not subject to flammability limits like premixed-charge engines since there is a continuously range of fuel-to-air ratios varying from zero in the pure air to infinite in the pure fuel, thus someplace there is a stoichiometric ($\phi = 1$) mixture that can burn. Such variation in $\phi$ does not occur in premixed-charge engines since, by definition, $\phi$ is the same everywhere.
So why would anyone want to use a premixed-charge engine?

Because the nonpremixed-charge engine burns its fuel slower, since fuel and air must mix before they can burn. This is already taken care of in the premixed-charge engine. This means lower engine RPM and thus less power from an engine of a given displacement.

Wait - you said that the premixed-charge engine is slower burning.

Only if the mixture is too lean. If it's near-stoichiometric, then it's faster because, again, mixing was already done before ignition (ideally, at least). Recall that as $\phi$ drops, $T_{ad}$ drops proportionately, and burning velocity ($S_L$) drops exponentially as $T_{ad}$ drops.

Couldn't I operate my non-premixed charge engine at overall stoichiometric conditions to increase burning rate?

No. In nonpremixed-charge engines it still takes time to mix the pure fuel and pure air, so (as discussed previously) burning rates, flame lengths, etc. of nonpremixed flames are usually limited by mixing rates, not reaction rates. Worse still, with initially unmixed reactants at overall stoichiometric conditions, the last molecule of fuel will never find the last molecule of air in the time available for burning in the engine - one will be in the upper left corner of the cylinder, the other in the lower right corner. That means unburned or partially burned fuel would be emitted. That's why diesel engines smoke at heavy load, when the mixture gets too close to overall stoichiometric.
So what wrong with operating at a maximum fuel to air ratio a little lean of stoichiometric?

That reduces maximum power, since you're not burning every molecule of O\(_2\) in the cylinder. Remember - O\(_2\) molecules take up a lot more space in the cylinder that fuel molecules do (since each O\(_2\) is attached to 3.77 N\(_2\) molecules), so it behooves you to burn every last O\(_2\) molecule if you want maximum power. So because of the mixing time as well as the need to run overall lean, Diesels have less power for a given displacement / weight / size / etc.

So is the only advantage of the Diesel the better efficiency at part-load due to absence of throttling loss?

No, you also can go to higher compression ratios, which increases efficiency at any load. This helps alleviate the problem that slower burning in Diesels means lower inherent efficiency (more burning at increasing cylinder volume)

Why can the compression ratio be higher in the Diesel engine?

Because you don't have nearly as severe problems with knock. That's because you compress only air, then inject fuel when you want it to burn. In the premixed-charge case, the mixture being compressed can explode (since it's fuel + air) if you compress it too much
Ronney's catechism (4/4)

- Why is knock so bad?
  - It causes intense pressure waves that rattle the piston and leads to severe engine damage

- So, why have things evolved such that small engines are usually premixed-charge, whereas large engines are nonpremixed-charge?
  - In small engines (lawn mowers, autos, etc.) you're usually most concerned with getting the highest power/weight and power/volume ratios, rather than best efficiency (fuel economy). In larger engines (trucks, locomotives, tugboats, etc.) you don't care as much about size and weight but efficiency is more critical

- But unsteady-flow aircraft engines, even large ones, are premixed-charge, because weight is always critical in aircraft
  - You got me on that one. But of course most large aircraft engines are steady-flow gas turbines, which kill unsteady-flow engines in terms of power/weight and power/volume.
**Knock - what is it?**

- Occurs when the combination of piston compression + “flame compression” increases temperature and pressure of the end gas until a very rapid explosion.
- Engine combustion is always “horse race” between flame propagation (good horse) and knock (bad horse).

![Diagram showing Knock](image)

- **Burned gas**
- **End gas (unburned)**
- **Spark plug**
- **Direction of flame propagation**
- **Flame front**
Knock - movies

No knock

Knock

Videos courtesy Prof. Yuji Ikeda, Kobe University
Knock - why is it bad?

- Pressure gradients cause enormous stresses on the piston
- As the shocks propagate into the narrow region between the piston and cylinder wall (the “crevice volume”), the shock strength increases, causing locally even more severe damage

http://www.llnl.gov/str/Westbrook.html
Knock

- Shock formation causes “ringing” of pressure waves back & forth across cylinder - sounds like you're hitting piston with a hammer, which isn't too far from the truth

Basic gas turbine cycle
Turbofan
Solid / liquid rockets

Solid

Liquid
Why gas turbines?

- GE CT7-8 turboshift (used in helicopters)
  - Compressor/turbine stages: 6/4
  - Diameter 26”, Length 48.8” = 426 liters = 5.9 hp/liter
  - Dry Weight 537 lb, max. power 2,520 hp (power/wt = 4.7 hp/lb)
  - Pressure ratio at max. power: 21 (ratio per stage = 21\(^{1/6}\) = 1.66)
  - Specific fuel consumption at max. power: 0.450 (units not given; if lb/hp-hr then corresponds to 29.3% efficiency)

- Cummins QSK60-2850 4-stroke 60.0 liter (3,672 in\(^3\)) V-16 2-stage turbocharged diesel (used in mining trucks)
  - 2.93 m long x 1.58 m wide x 2.31 m high = 10,700 liters = 0.27 hp/liter
  - Dry weight 21,207 lb, 2850 hp at 1900 RPM (power/wt = 0.134 hp/lb = 35x lower than gas turbine)
  - Volume compression ratio ??? (not given)
Why gas turbines?

- Lycoming IO-720 11.8 liter (720 cu in) 4-stroke 8-cyl. gasoline engine (http://www.lycoming.com/engines/series/pdfs/Specialty%20insert.pdf)
- Total volume 23” x 34” x 46” = 589 liters = 0.67 hp/liter
- 400 hp @ 2650 RPM
- Dry weight 600 lb. (power/wt = 0.67 hp/lb = 7x lower than gas turbine)
- Volume compression ratio 8.7:1 (= pressure ratio 20.7 if isentropic)

- Ballard HY-80 “Fuel cell engine”
  - http://www.ballard.com/resources/transportation/XCS-HY-80_Trans.pdf (no longer valid link!)
  - Volume 220 liters = 0.41 hp/liter
  - 91 hp, 485 lb. (power/wt = 0.19 hp/lb)
  - 48% efficiency (fuel to electricity)
  - Uses hydrogen only - NOT hydrocarbons
  - Does NOT include electric drive system (≈ 0.40 hp/lb) at ≈ 90% electrical to mechanical efficiency (http://www.gm.com/company/gmability/adv_tech/images/fact_sheets/hywire.html) (no longer valid)
  - Fuel cell + motor overall 0.13 hp/lb at 43% efficiency, not including H₂ storage
Why gas turbines?

- Why does gas turbine have much higher power/weight & power/volume than recips? **More air can be processed** since steady flow, not start/stop of reciprocating-piston engines
  - More air ⇒ more fuel can be burned
  - More fuel ⇒ more heat release
  - More heat ⇒ more work (if thermal efficiency similar)

- What are the disadvantages?
  - Compressor is a **dynamic** device that makes gas move from low pressure to high pressure without a positive seal like a piston/cylinder
    - Requires very precise aerodynamics
    - Requires blade speeds ≈ sound speed, otherwise gas flows back to low P faster than compressor can push it to high P
    - Each stage can provide only 2:1 or 3:1 pressure ratio - need many stages for large pressure ratio
  - Since steady flow, each component sees a constant temperature - at end of combustor - **turbine stays hot continuously and must rotate at high speeds (high stress)**
    - Severe materials and cooling engineering required (unlike recip, where components only feel **average gas temperature during cycle**)
    - Turbine inlet temperature limit ≈ 1600K = 2420°F - limits fuel input
Why gas turbines?

- As a result, turbines require more maintenance & are more expensive for same power (so never used in automotive applications… but is used in modern military tanks, because of power/volume, NOT power/weight)
Survey question #1

Which fuel contains the most energy per kilogram?

a. Gasoline
b. Diesel
c. Jet fuel
d. They're all the same
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Survey question #2

Of jet engines (gas turbines), diesel engines and gasoline engines, which provides the most power per kilogram?

a. Jet > diesel > gasoline
b. Diesel > jet > gasoline
c. Gasoline > diesel > jet
d. Jet > gasoline > diesel
e. Diesel > gasoline > jet
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Survey question #3

What will be the most commonly used vehicle energy storage media 20 years from now?

a. Batteries
b. Hydrogen
c. Solar
d. Biofuel (e.g. ethanol or bio-diesel)
e. Conventional gasoline or diesel
f. Something else (don't tell anyone except me)
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