2.61 Internal Combustion Engines
Spring 2008

Assessment of Future Automotive Power Plant Technology

Fuel and engine alternatives

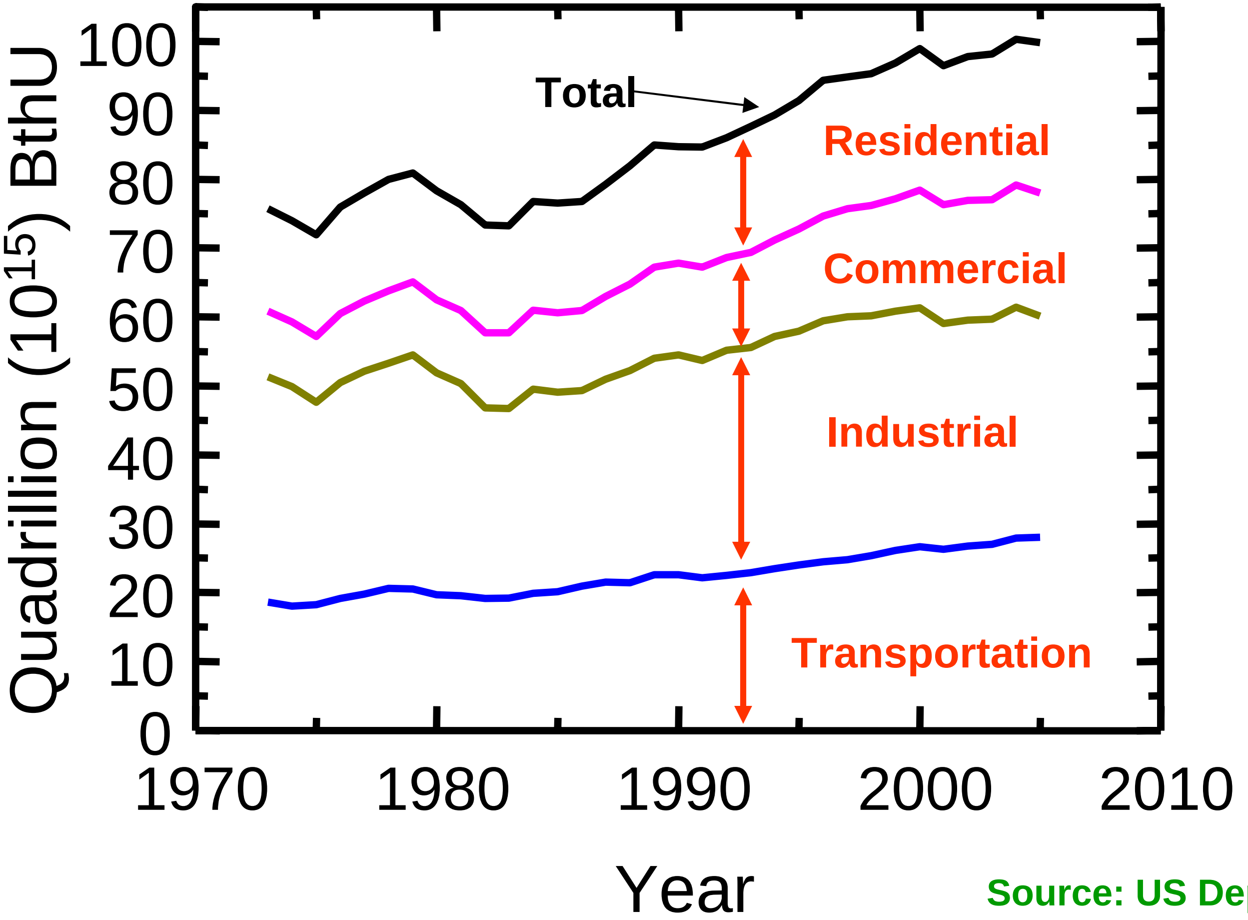
Prof. Wai K. Cheng
Sloan Automotive Lab
Massachusetts Institute of Technology

Transportation/Mobility

- Transportation/mobility is a vital to modern economy
  - Transport of People
  - Transport of goods and produce
- People get accustomed to the ability to travel

Transportation takes energy

US use of energy per year by sectors



Source: US Dept. of Energy

Transportation needs special kind of energy source

- Vehicles need to carry source of energy on board
- Hydrocarbons are unparalleled in terms of energy density
  - For example, look at refueling of gasoline
    - ~10 gallon in 2 minutes (~0.25 Kg/sec)
  - Corresponding energy flow

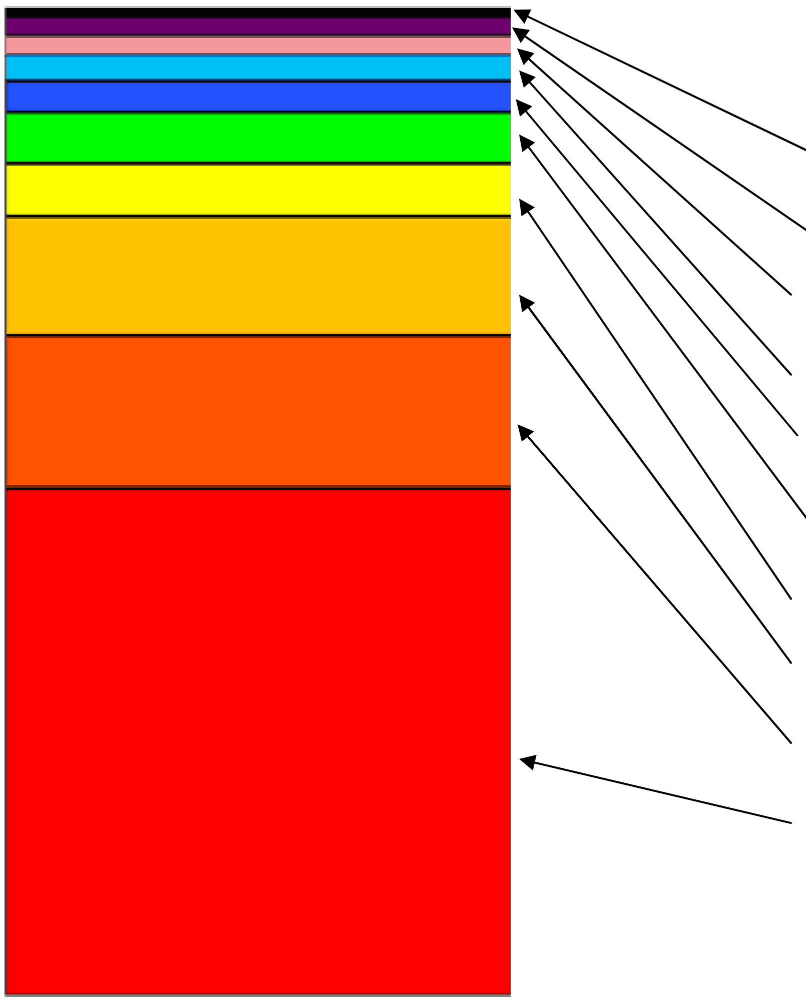
    = 0.25 Kg/sec x 44 MJ/Kg

    = 11 Mega Watts

Petroleum !

What is in a barrel of oil ?

(42 gallon oil → ~46 gallon products)

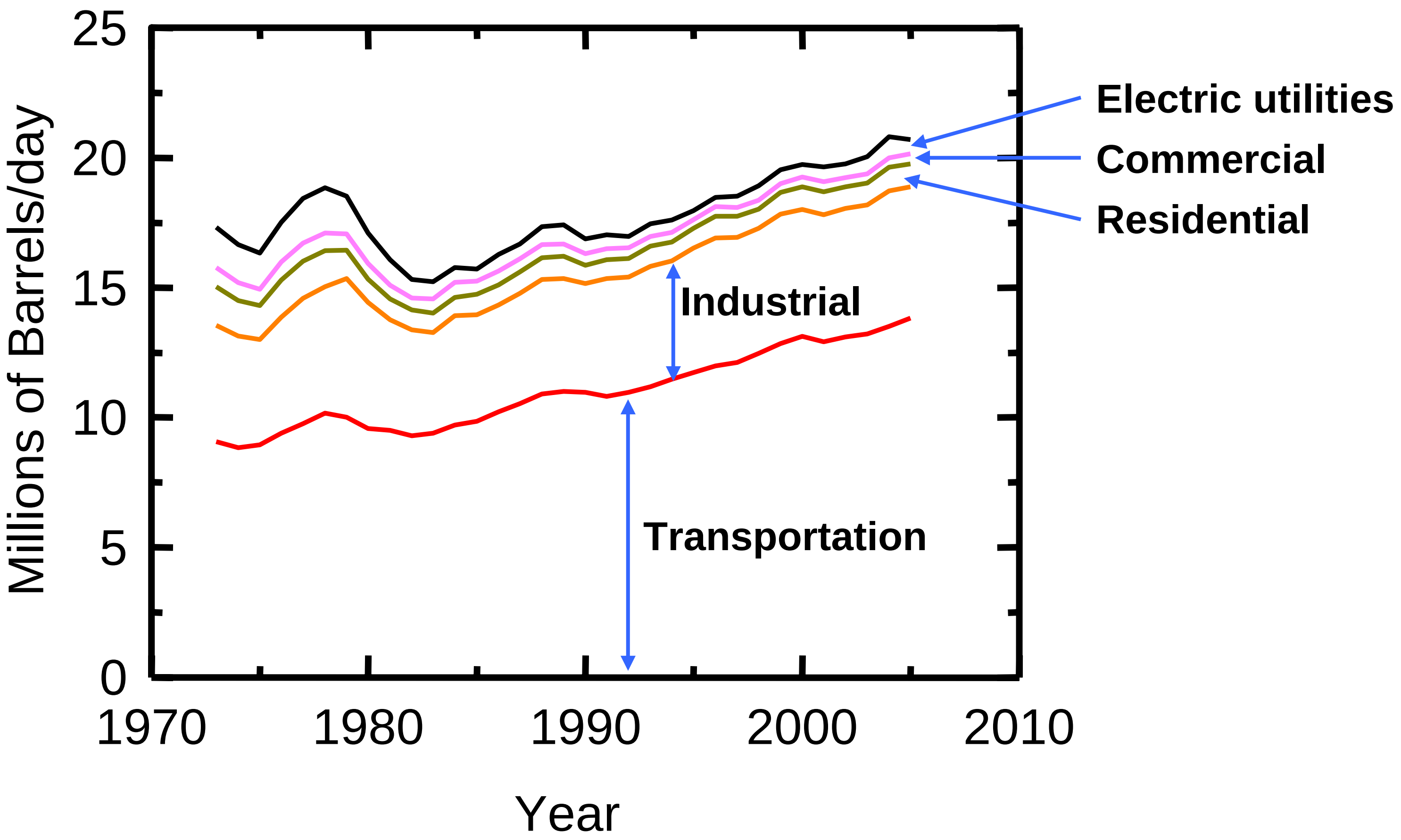


Typical US output

Lubricants	**0.90%**
Other Refined Products	**1.50%**
Asphalt and Road Oil	**1.90%**
Liquefied Refinery Gas	**2.80%**
Residual Fuel Oil	**3.30%**
Marketable Coke	**5.00%**
Still Gas	**5.40%**
Jet Fuel	**12.60%**
Distillate Fuel Oil	**15.30%**
Finished Motor Gasoline	**51.40%**

Source: California Energy Commission, Fuels Office

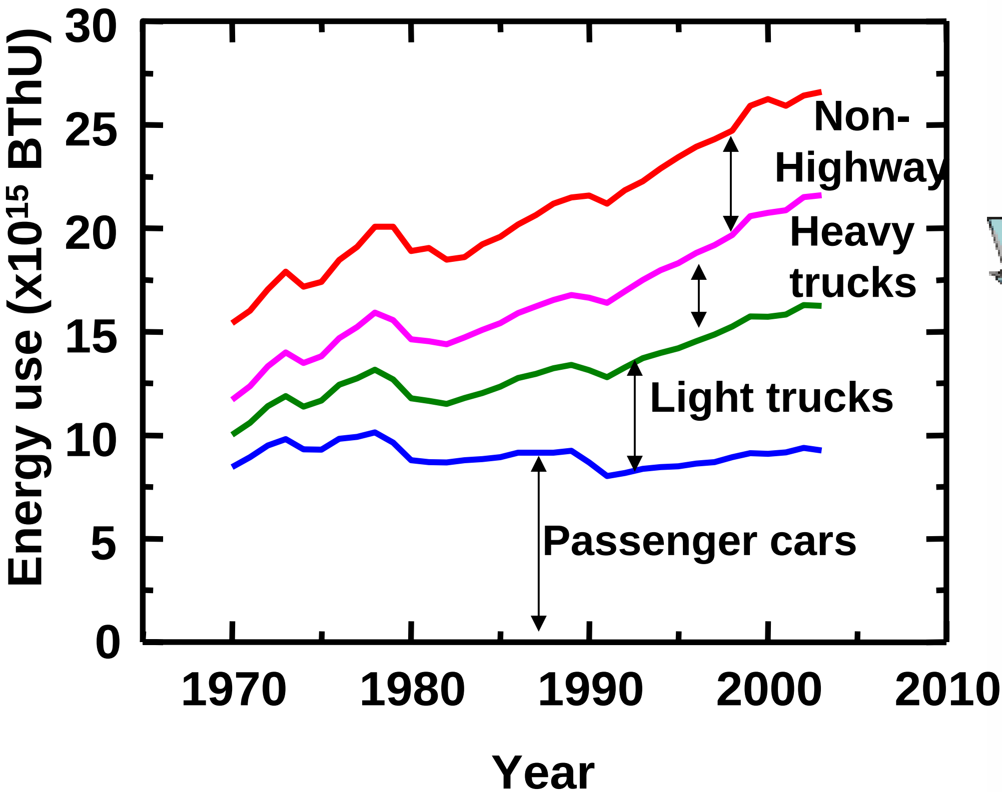
US Use of Petroleum by sector

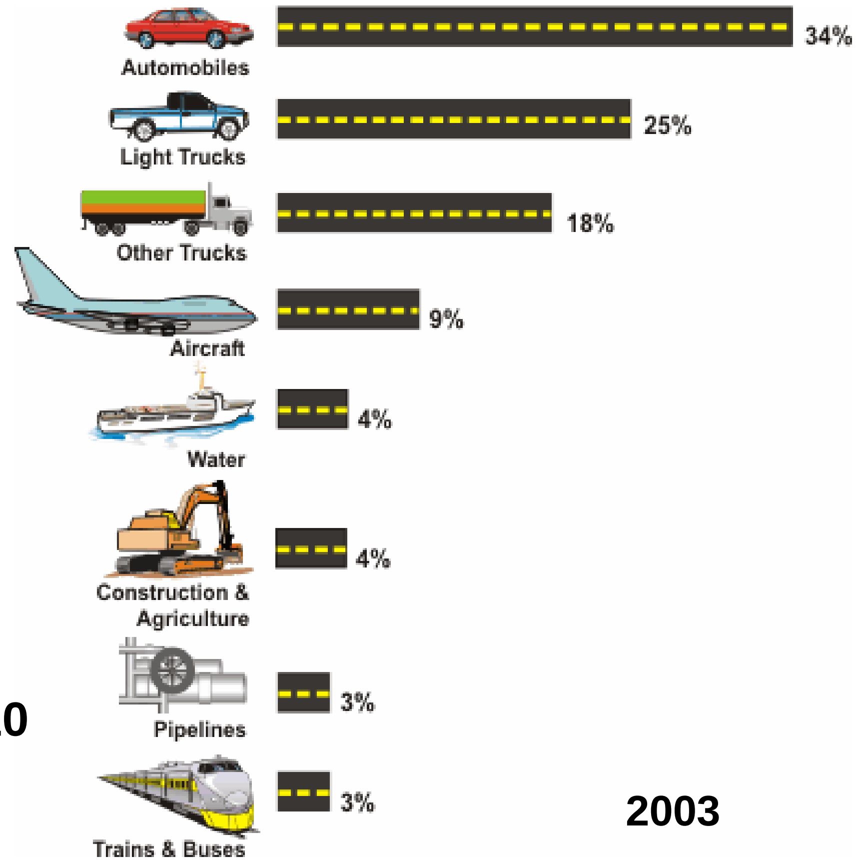


Source: US Dept. of Energy

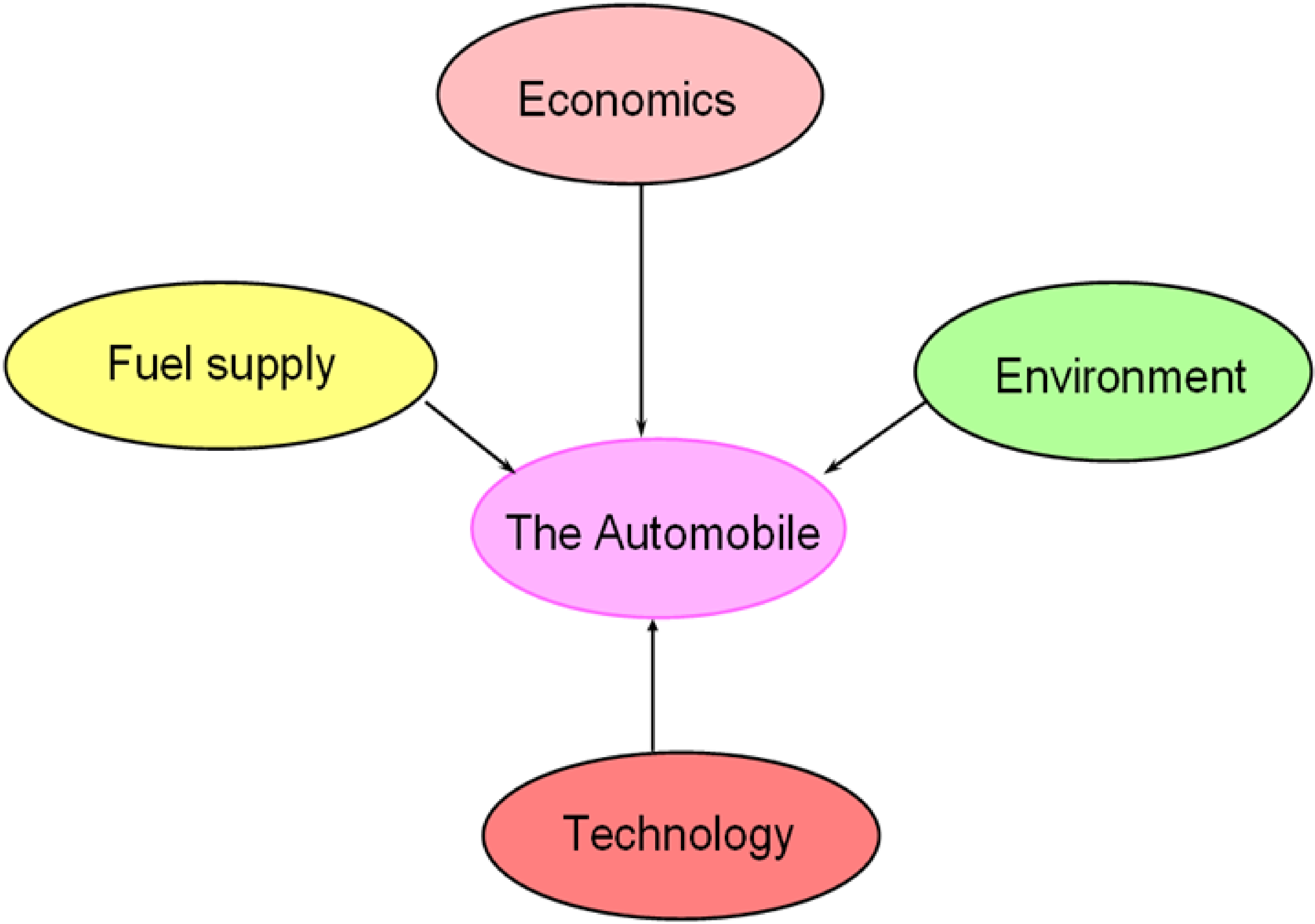
Transportation energy use

(does not include military transportation)





Source: US Dept. of Energy, *Transportation Energy Data Book*: Edition 26-2007.


Economics
Fuel supply
Environment
The Automobile
Technology

Size of the Automotive Industry

- Sales (US) ~ 18 millions new vehicles/year
- Approximately 72,000 vehicles produced per day (1.2 seconds / vehicle)

PRODUCT HAS TO BE ECONOMICALLY VIABLE ON ITS OWN

- High capital cost in manufacturing
- ~$3 Billion or more for a new line

NEED HIGH VOLUME TO MAKE MONEY

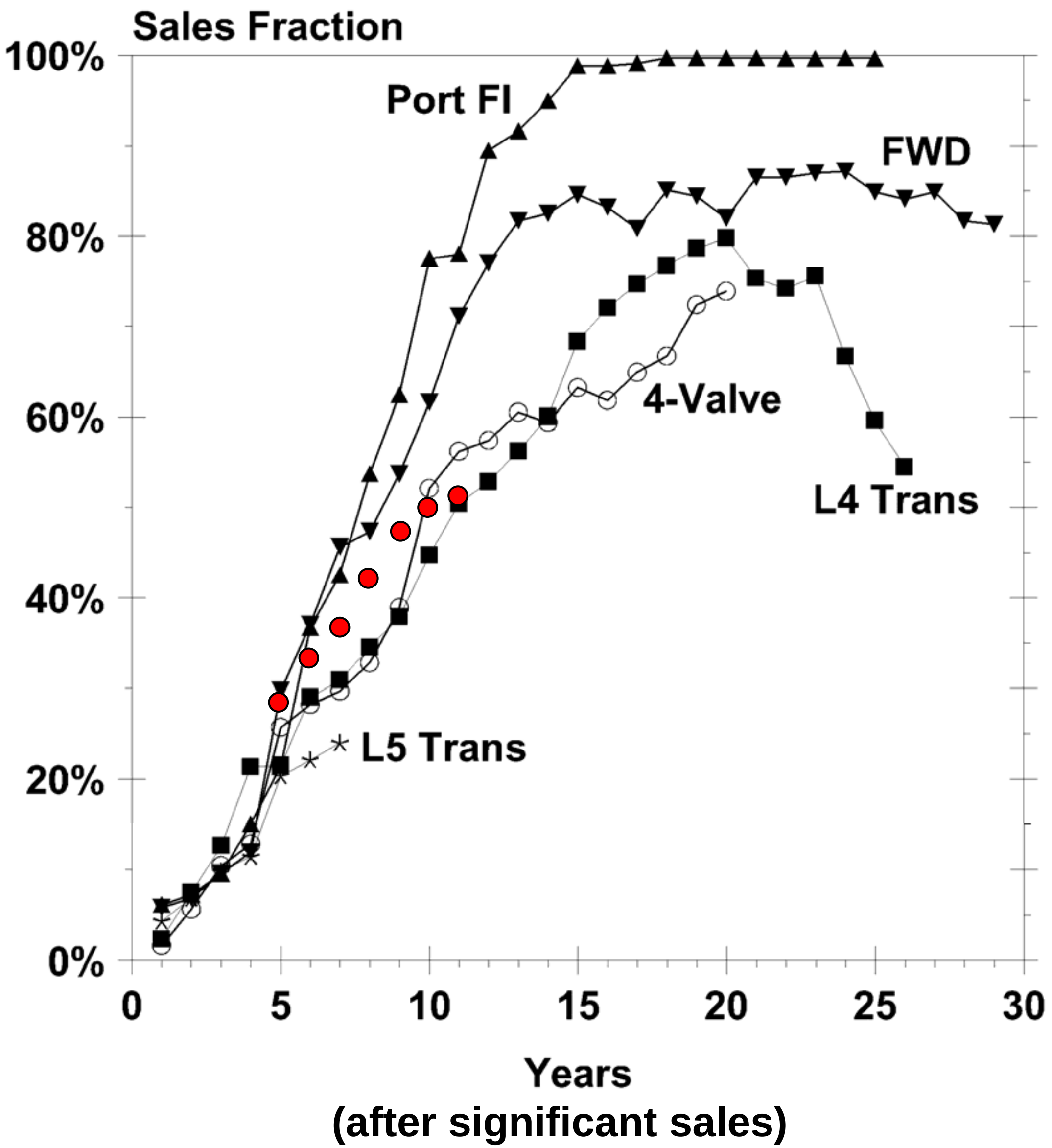
Petroleum Industry

Very capital intensive

- Exploration and production
- Refinery
- Distribution system

“Inertia” of the industry

- Utilization of capital
  - Need for capital expense to depreciate
- Technology takes time to develop and implemented
  - Example: vehicle powertrain
    a. Incremental changes: Design needs to be completed 3-4 years before production
    b. Significant changes: Add 5-10 years of development time to (a)
    c. Drastic changes: Add 15 to 20 years to (a)
    d. Radical changes: Add ? years to (a)
- Market penetration



Technology penetration

- Diesel sales fraction in Europe 1999-2005. (DI diesel introduced in 1997; sales fraction constant at 14% from 1987-1991.) Source: DOE

Source: Heavenrich, "Light-Duty Automotive Technology and Fuel Economy Trends, 1975-2005", EPA420-R-05-001

CUSTOMER NEEDS

VEHICLE

- Reasonable Cost
- Reliability
- Comfort
- Performance
- Aesthetics - Look and Feel

FUEL

- Cost
- Availability
- Ease of refueling

ENVIRONMENTAL IMPACT

- Air quality
  - NOx
  - CO
  - Ozone
  - Particulate matters
  - Toxics
- Noise
- Green House Effect (CO2, methane)
  - Kyoto Agreement (USA): 7% reduction of CO_2 from 1990 level
- Congestion

FUELS

- Reformulated Gasoline
- Methanol
- Ethanol and other bio-fuels
- Hydrogen

Transportation Fuels

Fuels	Density	LHV/mass*	LHV/Vol.**	LHV/Vol. of Stoi.Mixture @1 atm, 300K***
	(Kg/m^3)	(MJ/Kg)	(MJ/m^3)	(MJ/m^3)
Gasoline	750	44	3.3×10^4	3.48
Diesel	810	42	3.4×10^4	3.37
Natural Gas				
@1 bar	0.72	45	3.2×10^1(x)	3.25
@100 bar	71		3.2×10^3	
LNG (180K, 30bar)	270		1.22×10^4	
Methanol	792	20	1.58×10^4	3.19
Ethanol	785	26.9	2.11×10^4	3.29
Hydrogen				
@1bar	0.082	120	0.984×10^1(x)	2.86
@100 bar	8.2		0.984×10^3	
Liquid (20K, 5 bar)	71		8.52×10^3	

*Determines fuel mass to carry on vehicle
**Determines size of fuel tank
***Determines size of engine

Relative CO2 production from different fuel molecules

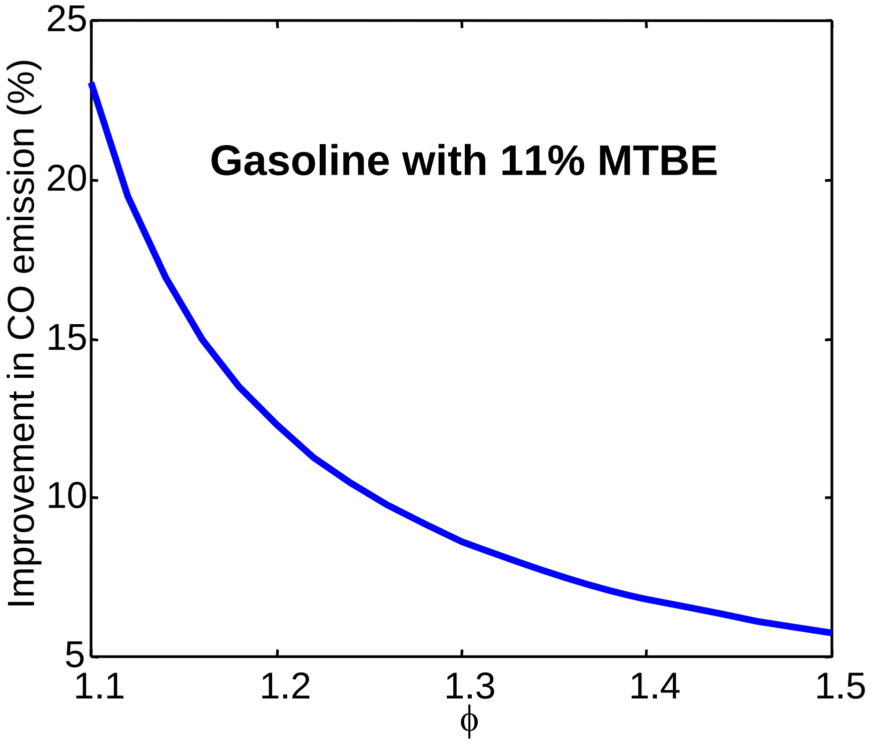
Image removed due to copyright restrictions. Please see Amann, Charles A. “The Passenger Car and The Greenhouse Effect.” *SAE Journal of Passenger Cars* 99 (October 1990): 902099.

C. Amann, SAE Paper 9092099

REFORMULATED FUELS

- Modify fuel properties to improve air quality (does not significantly impact CO2 emissions)
- Introduce oxygenates (MTBE, ethanol, etc.) in gasoline to lower CO and HC emissions (US: 2% oxygenate required)
- Lower sulfur content
  - improve catalyst performance in gasoline vehicles
  - lowers sulfate emissions in diesels
- Lower aromatic content to reduce toxic emissions
- Lower Reid vapor pressure in gasoline to reduce diurnal emissions

- **COMPATIBLE WITH CURRENT ENGINES IN EXISTING FLEET**



Note: for modern engine with λ feedback, oxygenate effect on emissions is minimal

ALTERNATIVE FUEL: METHANOL

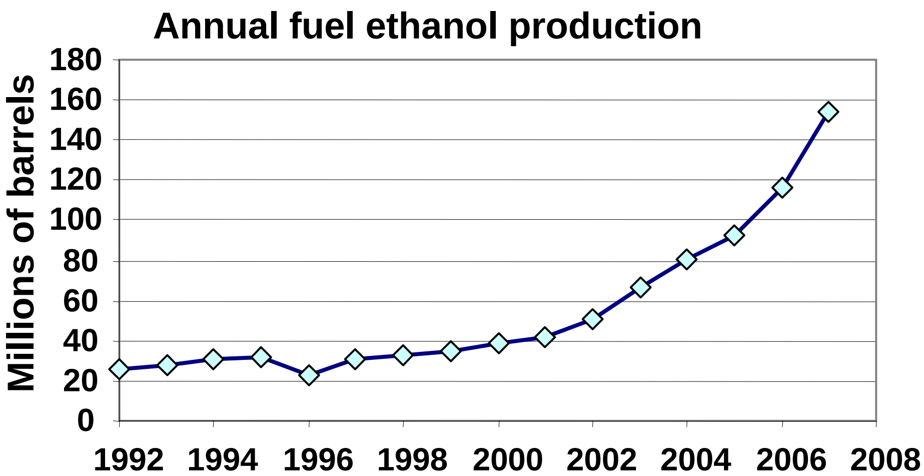
- GOOD COMBUSTION CHARACTERISTICS
  - High octane number (ON=99)
  - Cleaner exhaust: Lower CO and HC emissions
- PROBLEMS
  - Smaller heating value (~1/2 of that of gasoline)
  - toxic and corrosive
  - Difficulty in cold-start
- PRODUCTION - From natural gas and coal
  - Not efficient use of “original” fossil fuel: methanol is essentially a partially oxidized product
- **OUTLOOK**
  - Not an attractive intermediate alternatives because:
    - needs expensive retrofit of existing engine
  - Not good long term prospect; not efficient use of energy source

ALTERNATIVE FUEL: ETHANOL

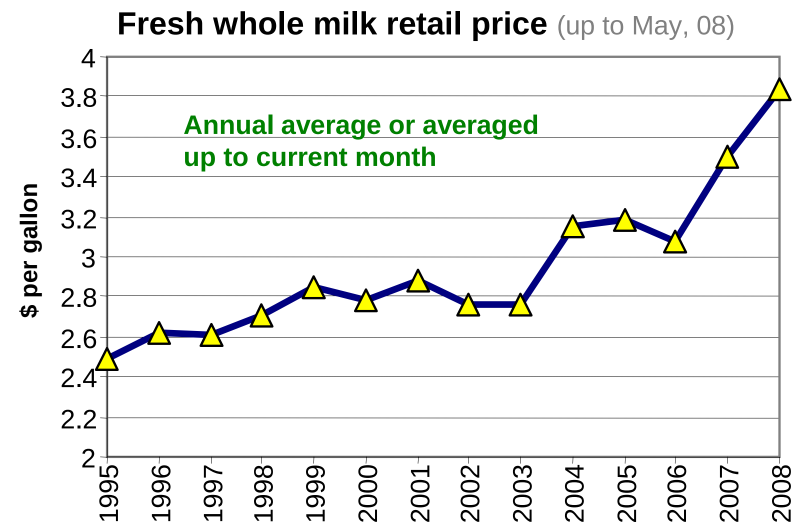
- **GOOD COMBUSTION CHARACTERISTICS**
  - High octane number (ON=107)
  - Cleaner exhaust: Lower CO for older vehicles
- **PROBLEMS**
  - Smaller heating value (61% of that of gasoline)
  - Water absorption/corrosion/volatility problem
  - Need special hardware
  - Difficulty in cold-start
- **PRODUCTION**
  - Mostly from starch crops (corn, barley, wheat etc.) by fermenting and distilling
  - Cellulosic ethanol (from tree, grass, etc.)
- **E85 (85 liq. vol. % ethanol) is used as a practical fuel**
- **Needs flexible fuel vehicle for practical operation because of uncertainty in fuel supply**

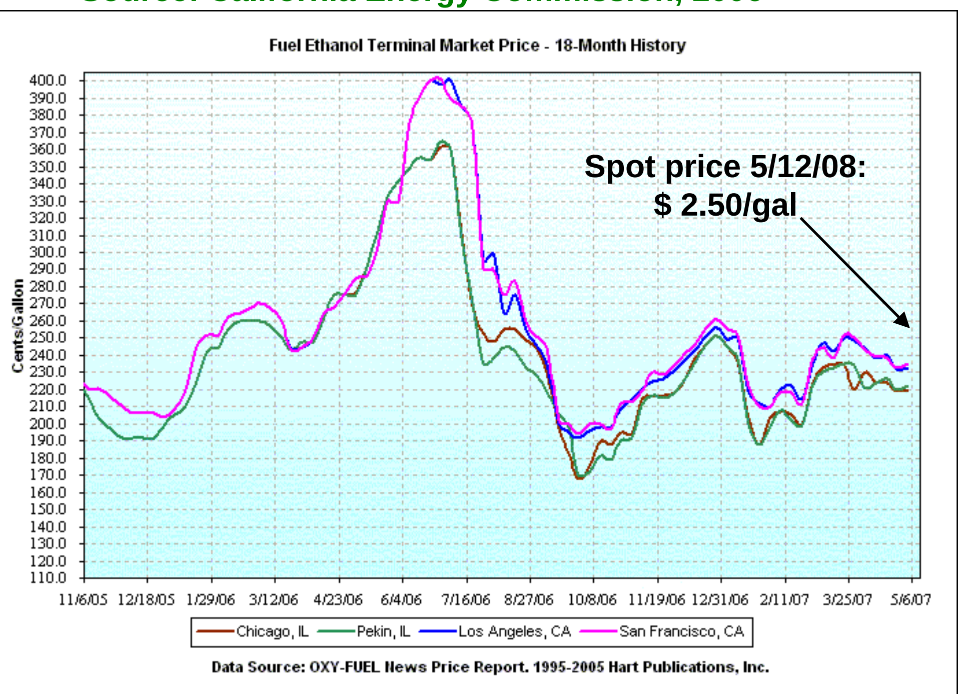
ALTERNATIVE FUEL:

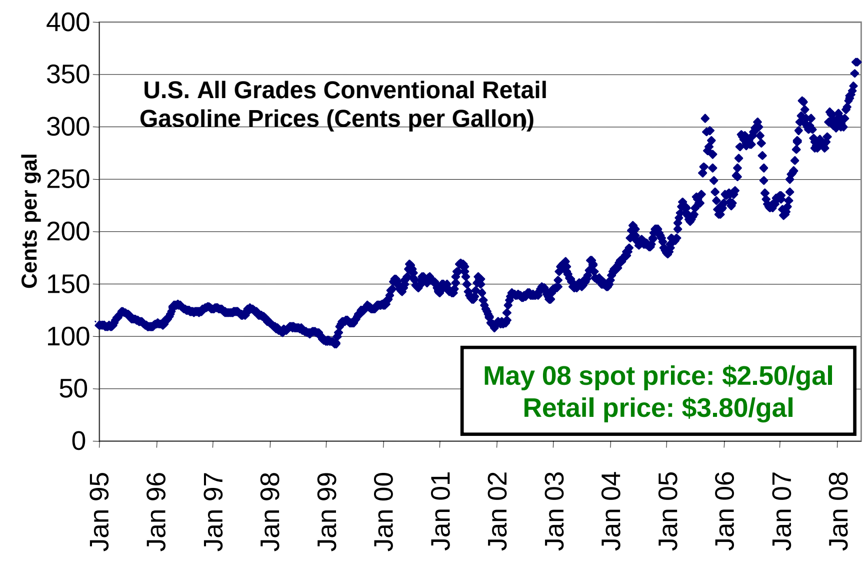
ETHANOL, bio-fuel for the future?



Source: California Energy Commission, 2006







ALTERNATIVE FUEL: ETHANOL
Bio-Fuel for the future?

- Current US demand for ethanol is driven by government regulations and incentives
  - Ethanol flex-fuel vehicles produced because of the 74% credit towards CAFE requirement
    - **(E85 vehicle equivalent mph = mpg x 1.74)**
  - Gasoline oxygenate mandate, and phase out of MTBE
  - Energy bill (Aug. 05) mandated a threshold of 7.5 billion gallons (180 million barrels) production by 2012
  - Tax subsidy
    - blender's tax credit $0.51/gallon alcohol
    - $0.051/gallon fuel tax exemption for gasohol
      - minimum 10 vol % alcohol

Is corn-based ethanol the bio-fuel of the future?

- **Substantial increase in US food price**

ALTERNATIVE FUEL: ETHANOL

Bio-Fuel for the future?

Ethanol from corn

- Several studies of the overall energy budget
  - P = energy used in production
    - ➢ feedstock production/ transport + processing
  - E = Energy of the ethanol output
  - Return (%) = (E – P) / E
- **Studies**
  - Pimentel and Patzek (2003, 2005): **negative return**
    - ➢ Return = **- 29%**
  - USDA (Shapouri et al 2002, 2004): **positive return**
    - ➢ Return* = **+5.6%**
    - ➢ Return* = **+40%** if by products (Corn gluten meal, etc.) are accounted for

Verdict: Substantial environmental and economic cost; return not clear

*** For comparison purpose, these figures were converted from the values of (E-P)/P of +5.9% and +67% in the original publication**

Other bio-fuels

- Pimentel and Patzek also estimated energy budget for other bio-fuels. Returns:
  - Ethanol from switchgrass = -50%
  - Ethanol from wood biomass = -57%
  - Bio-diesel from soybean = -27%
  - Bio-diesel from sunflower = -118%
- Outlook: NOT CLEAR
  - New technology needed to change the picture

ALTERNATIVE FUEL: HYDROGEN

- Excellent fuel for combustion engines or fuel cells
  - No green house gas emissions/ hydrocarbon emissions
- Strictly, hydrogen is not a “fuel”, but an energy storage medium
- Not an efficient use of the “original” energy source
  - Efficiency loss in generating and in using the hydrogen
- PROBLEMS
- Storage (cryogenic, high pressure cylinders, metal hydride matrix) - Bulky and expensive
  - At 200 bar storage pressure, pumping loss is 13% of LHV
- Infra-structure for fuel supply
- Safety
- **OUTLOOK**: not attractive
  - On-board hydrogen storage: not a desirable option
  - Hydrogen from fuel reforming
    - ➢ Complex process with efficiency loss
    - ➢ Does not alleviate green house gas

ENGINES

- Spark Ignition Engines
  - Good fuel efficiency, reasonable cost
  - Improving emissions characteristics
- Diesel Engines
  - Better fuel economy
  - higher cost
  - NOx / particulate emissions

- Electric/ Hybrid/ Plug-in-hybrid Vehicles
- Fuel Cell

Hybrid vehicles

Configuration:

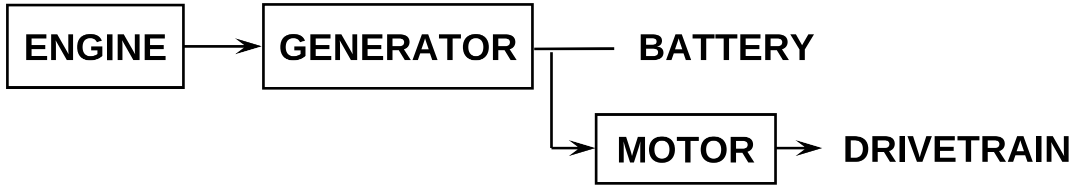
IC Engine + Generator + Battery + Electric Motor

Concept

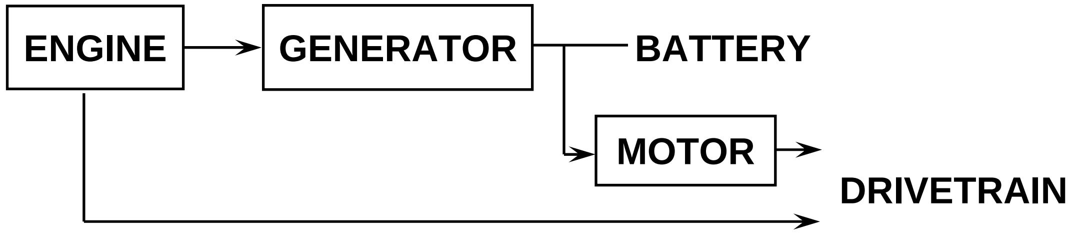
- Eliminates external charging
- As “load leveler”
  - Improved overall efficiency
- Regeneration ability
- Plug-in hybrids: use external electricity supply

Hybrid Vehicles

Series Hybrid



Parallel Hybrid



Examples: Toyota Prius (full hybrid); Honda Insight (electric assist)

Hybrid Vehicles: Market

- On the market since 1997 (Japan)
- Currently available in US:
  - Toyota Prius (~$20K)
  - Honda Insight, Civic Hybrid (~$19-20K)
  - Ford Escape ($27K)
  - …

Note:

No. of EV sold world wide since their introduction 30 years ago is < 30,000 units, and has flattened out

No. of Prius sold in three years(1997-2000)

➢ 34,000 units

Toyota Hybrid sale (2004) 130,000 units

(source: Toyota)

Toyota Prius

Honda Insight

Photos removed due to copyright restrictions. Please see any promotional photos of the Toyota Prius and the Honda Insight.

66/43 mpg on Japan/US driving cycle

80/60 mpg on Japan/US driving cycle

ELECTRIC HYBRID VEHICLE TECHNOLOGY

Toyota Prius

- Engine: 1.5 L, Variable Valve Timing, Miller Cycle (13.5 expansion ratio), Continuously Variable Transmission
  - 58 HP at 4000 rpm
- Motor - 40 HP
- Battery - Nickel-Metal Hydride, 288V
- Fuel efficiency:
  - 66 mpg (Japanese cycle)
  - 43 mpg (EPA city driving cycle)
  - 41 mpg (EPA highway driving cycle)
- Efficiency improvement (in Japanese cycle) attributed to:
  - 50% load distribution; 25% regeneration; 25% stop and go
- Cost: ~$20K (subsidized)

Cost factor

If $\Delta\$$ is price premium for hybrid vehicle
P is price of gasoline (per gallon)
δ is fractional improvement in mpg

Then mileage (M) to be driven to break even is

$$M = \frac{\Delta\$ \text{ x mpg}}{P \text{ x } \delta}$$

(assume that interest rate is zero)

Cost Factor

Example:

Honda Civic and Civic-Hybrid

Price premium (Δ$, MY08 listed) = $7155 **($22600-15445)**

mpg (city and highway av.) = 29 mpg (42 for hybrid)

hybrid improvement in mpg(%) = 45%

At gasoline price of $4.00 per gallon, mileage (M) driven to break even is

$$M = \frac{\$7155 \times 29}{\$4 \times 45\%} = 115{,}000 \text{ miles}$$

(excluding interest cost)

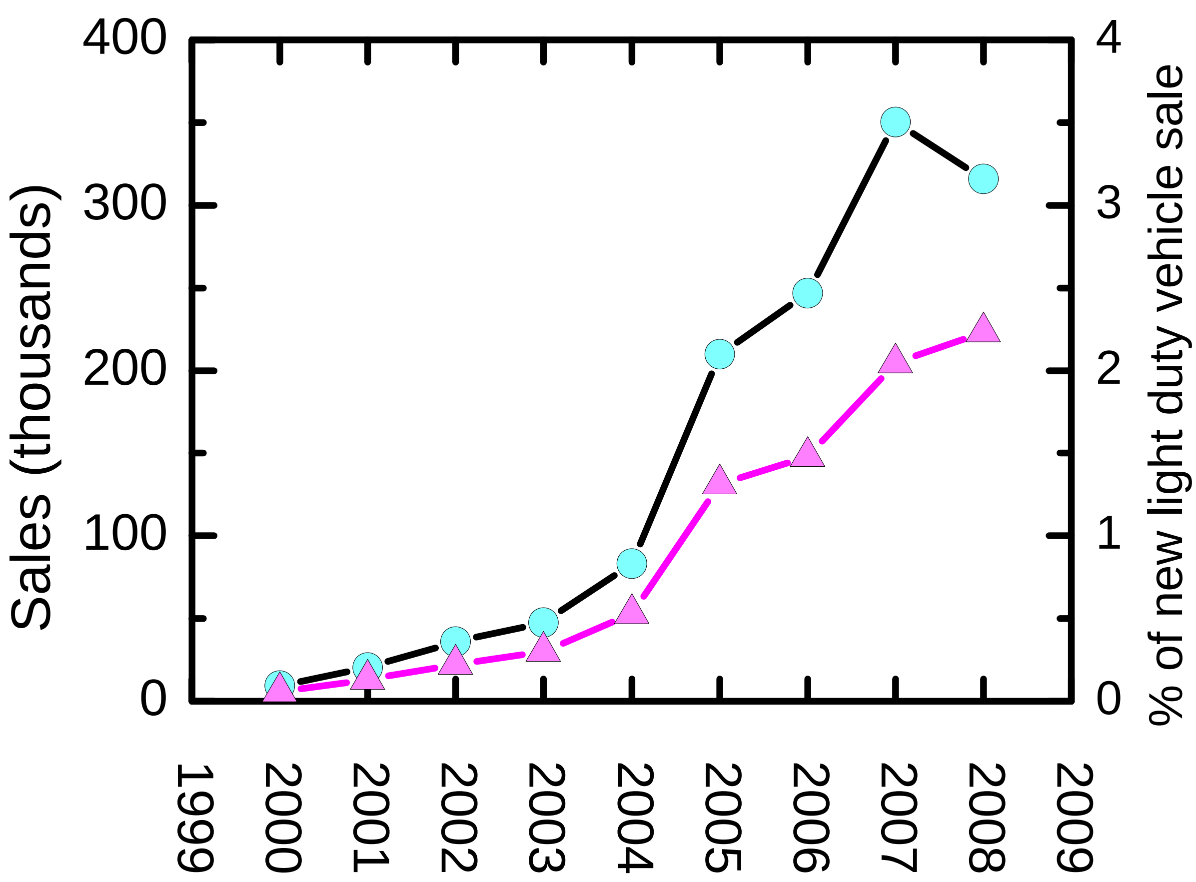
Barrier to Hybrid Vehicles

- Cost factor
  - difficult to justify especially for the small, already fuel efficient vehicles
- Battery replacement **(not included in the previous breakeven analysis)**
  - California ZEV mandate, battery packs must be warranted for 15 years or 150,000 miles : a technical challenge

Hybrid Vehicle Outlook

- Hybrid configuration will capture a fraction of the passenger market, especially when there is significant fuel price increase
- Competition
  - Customers downsize their cars
  - Small diesel vehicles
- Plug-in hybrids?
  - Weight penalty (battery + motor + engine)
  - No substantial advantage for overall CO_2 emissions
  - Limited battery life

Sales figure for hybrid vehicles

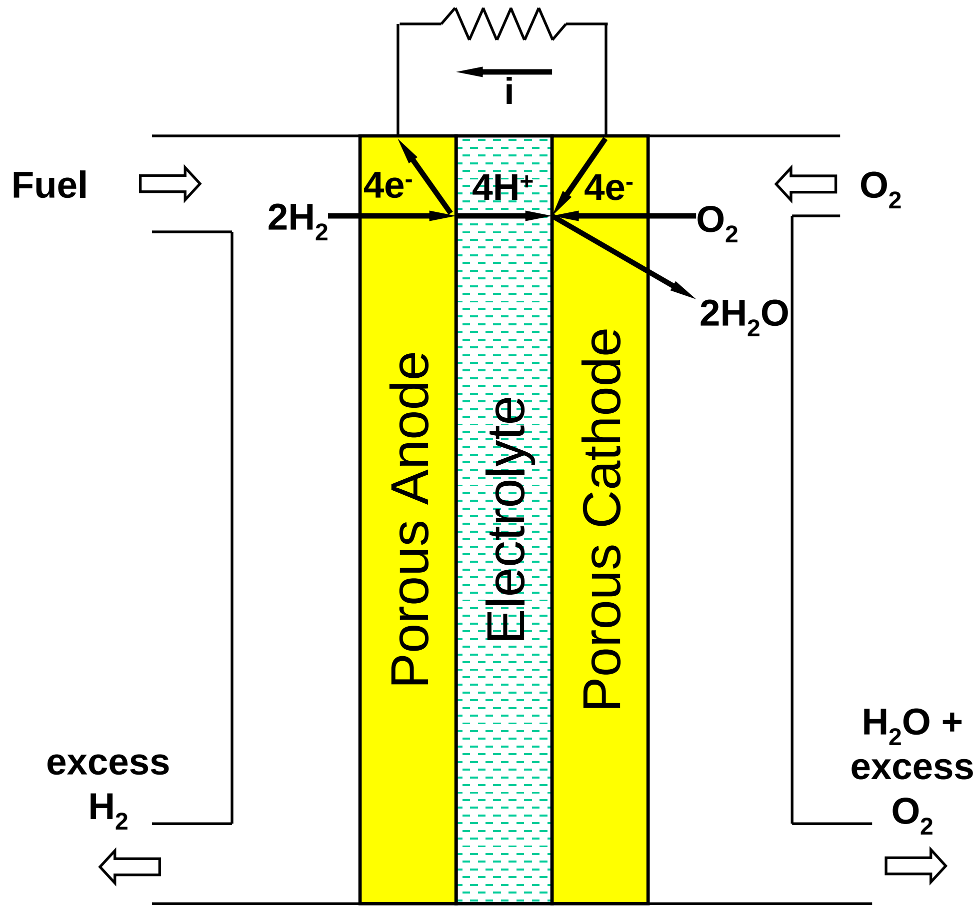


What is a fuel cell?

Direct conversion of fuel/oxidant to electricity

- $2H_2 + O_2 \rightarrow 2H_2O$
- Potentially much higher efficiency than IC engines

H_2 - O_2 system



History of Fuel Cell

- **Sir William Grove** demonstrated the first fuel cell in 1839 (H_2 – O_2 system)

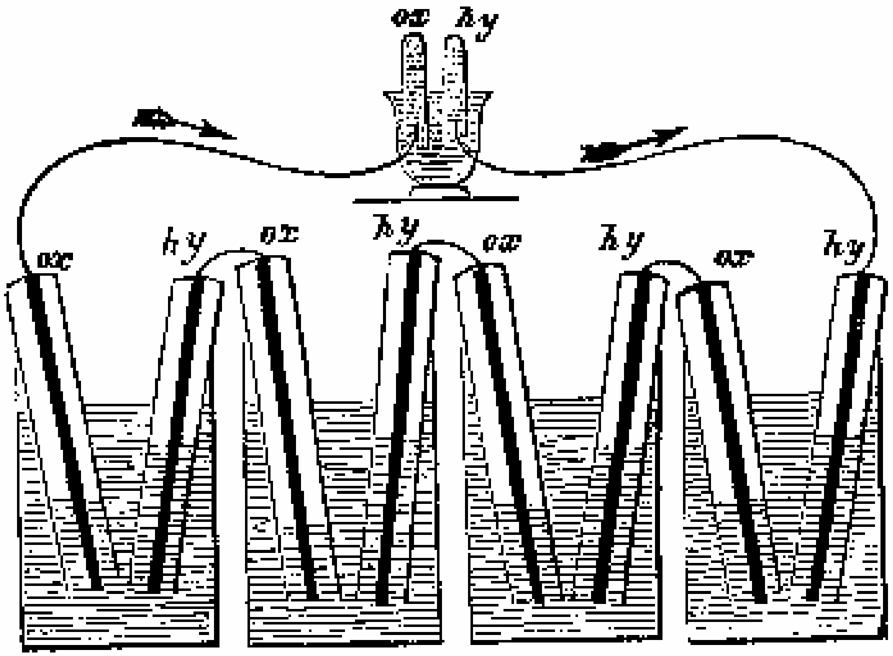
- Substantial activities in the late 1800's and early 1900's
  - Theoretically basis established
    - Nerst, Haber, Ostwald and others

- Development of Ion Exchange Membrane for application in the Gemini spacecraft in the 1950/1960
  - W.T. Grubb (US Patent 2,913,511, 1959)

- Development of fuel cell for automotive use (1960's to present)

The Grove Cell (1839)

- Important insights to fuel cell operation
  - H2-O2 system (the most efficient and the only practical system so far)
  - Platinum electrodes (role of catalyst)
  - recognize the importance of the coexistence of reactants, electrodes and electrolyte



W.R.Grove, 'On Gaseous Voltaic Battery," Pil. Mag., **21**,3,1842
As appeared in Liebhafsky and Cairns, *Fuel Cells and Fuel Batteries*, Wiley, 1968

Types of fuel cell

- Classification by fuel
  - Direct conversion
    - ➢Hydrogen/air (pre-dominant)
    - ➢Methanol/air (under development; electrode poisoning problem)
  - Indirect conversion
    - ➢reform hydrocarbon fuels to hydrogen first
- Classification by charge carrier in electrolyte
    - ➢H^+, O^{2-} (important difference in terms of product disposal)

Types of fuel cell (cont.)

- By electrolyte
  - Solid oxides: ~1000^{o}C
  - Carbonates: ~600^{o}C
  - H_3PO_4: ~200^{o}C
  - Proton Exchange Membrane (PEM): ~80^{o}C

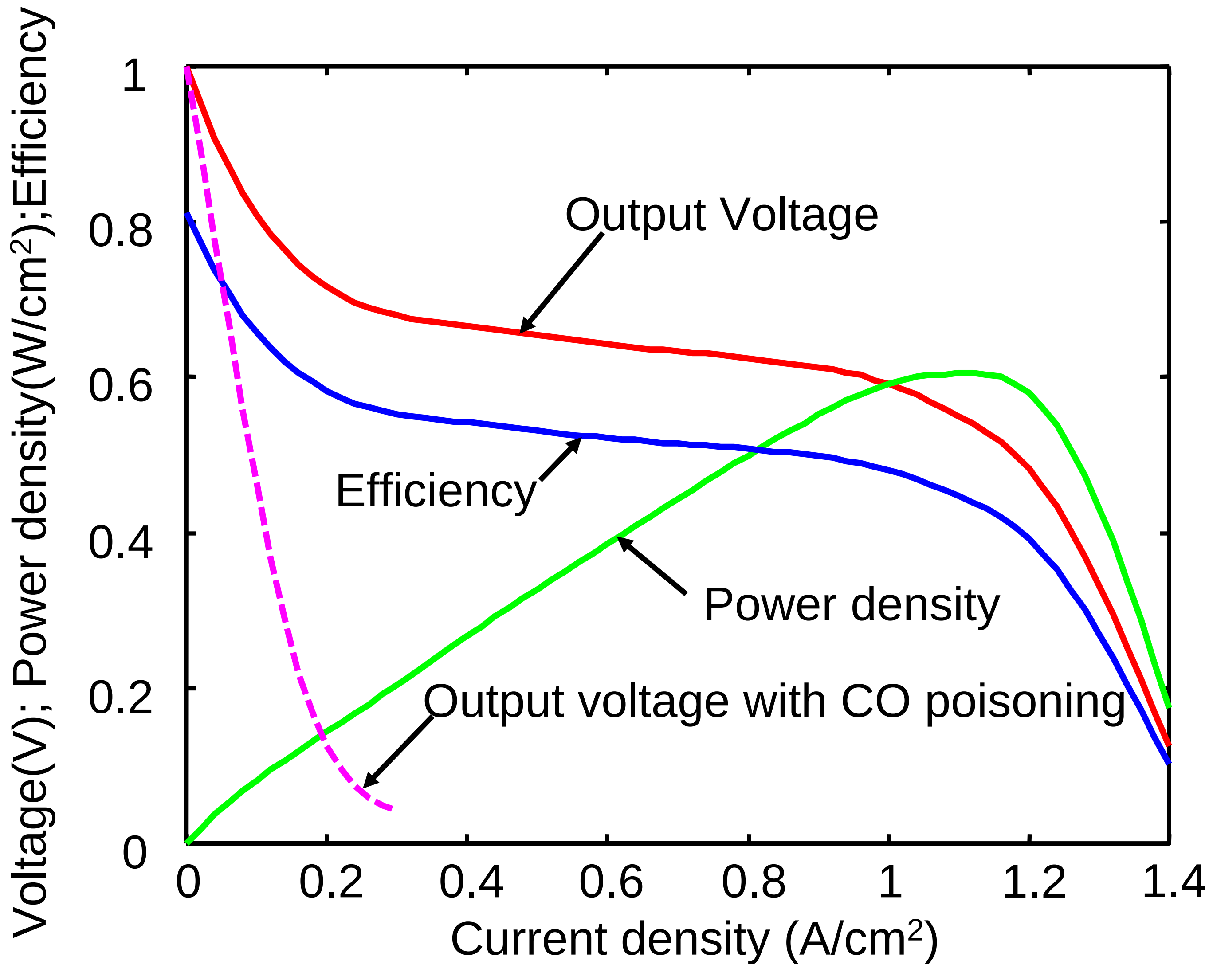
Automotive application

Modern PEM fuel cell stack

Diagram of a PEM fuel cell stack removed due to copyright restrictions.
Please see http://www.technopr.com/download/Figure1-FuelCellConstruction.jpg

(From 3M web site)

Current PEM H_2/O_2 Fuel Cell Performance



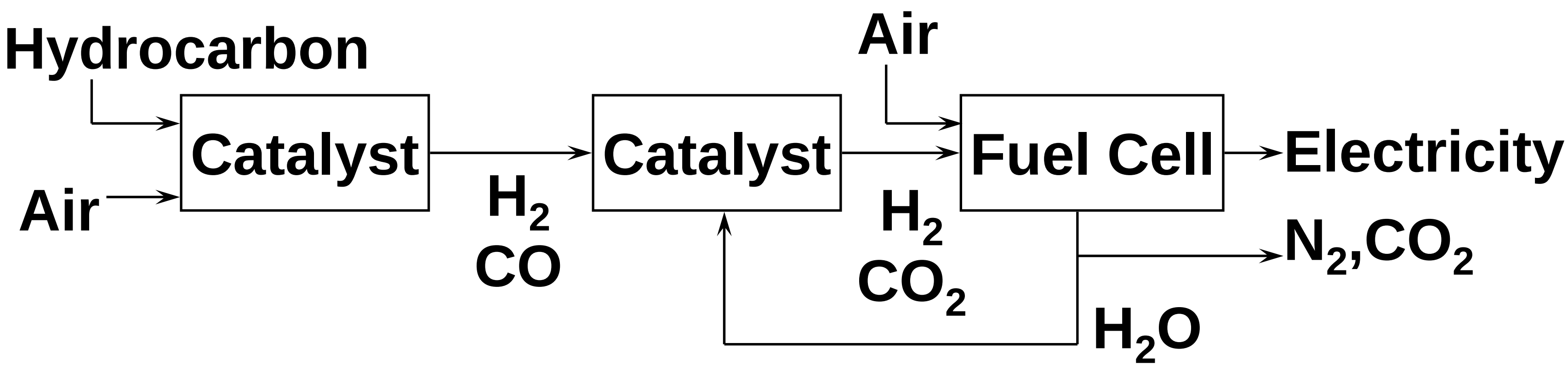
Note: Efficiency does not include power required to run supporting system

The Hydrogen problem:

Fundamentally H_2 is the only feasible fuel for fuel cell in the foreseeable future

- Strictly, hydrogen is not a “fuel”, but an energy storage medium
  - Difficulty in hydrogen storage
  - Difficulty in hydrogen supply infra structure
- Hydrogen from fossil fuel is NOT an efficient energy option
- Environmental resistance for nuclear and hydroelectric options

The hydrogen problem: H_2 from reforming petroleum fuel



Note: HC to H_2/CO process is exothermic; energy loss ~20% and needs to cool stream (Methanol reforming process is energy neutral, but energy loss is similar when it is made from fossil fuel)

Current best reformer efficiency is ~70%

Problems:

- CO poisoning of anode
- Sulfur poisoning
  - Anode poisoning requires S<1ppm
  - Reformer catalyst poisoning requires S<50ppb

Fuel cell powerplant with fuel reforming

Images removed due to copyright restrictions. Please see photos of the Chevrolet S-10 Gen III gasoline fuel cell vehicle, such as http://www.pickuptrucks.com/html/news/fuelcells10.html

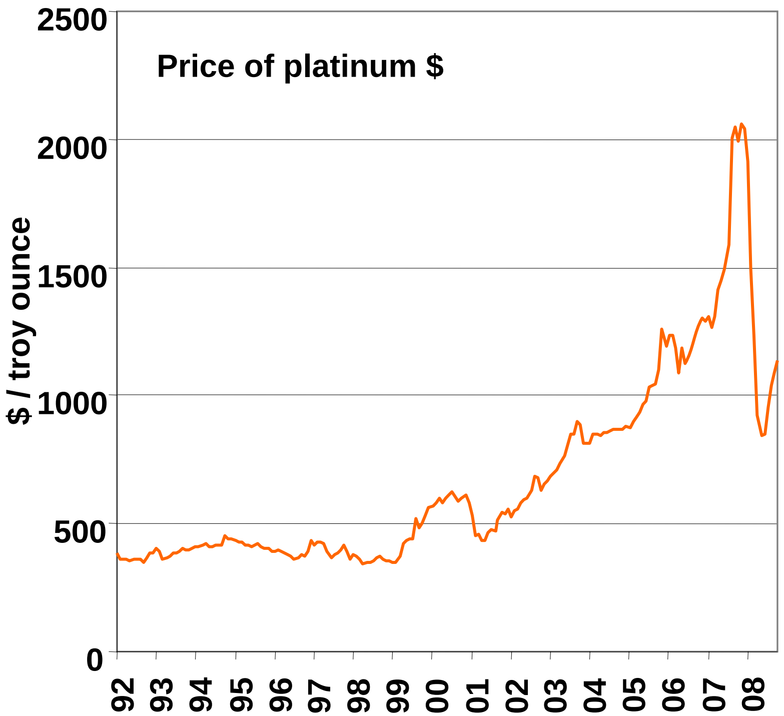
Practical Problems

Start up/shut down
Load Control
Ambient temperature
Durability

GM (May, 2002) Chevrolet S-10 fuel cell demonstration vehicle powered by onboard reformer

Fuel cell as automotive powerplant

- Current (2006) Fuel cell characteristics
  - $1 A/cm^2$, 0.5-0.7 V operating voltage
  - 0.5-0.7 W/cm^2 power density
  - stack power density 0.7 kW/L
  - Platinum loading ~0.3 mg/cm^2
    - ➢ 30g for a 60kW stack (2007 price ~$1300)
    - ➢ (automotive catalyst has ~2-3g)
  - System efficiency (with reformer) 30%
  - $600/kW (compared to passenger car at $10/kW)



Future of Petroleum fueled fuel cell

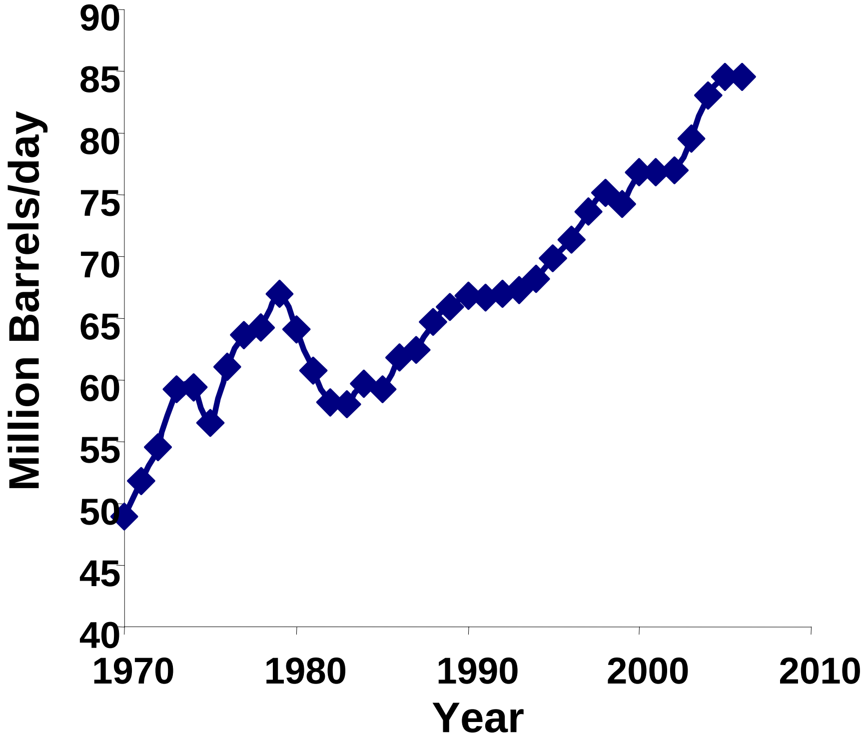
Is the emperor wearing any clothes?

- Not an attractive option:
  - Cost
  - Fuel utilization

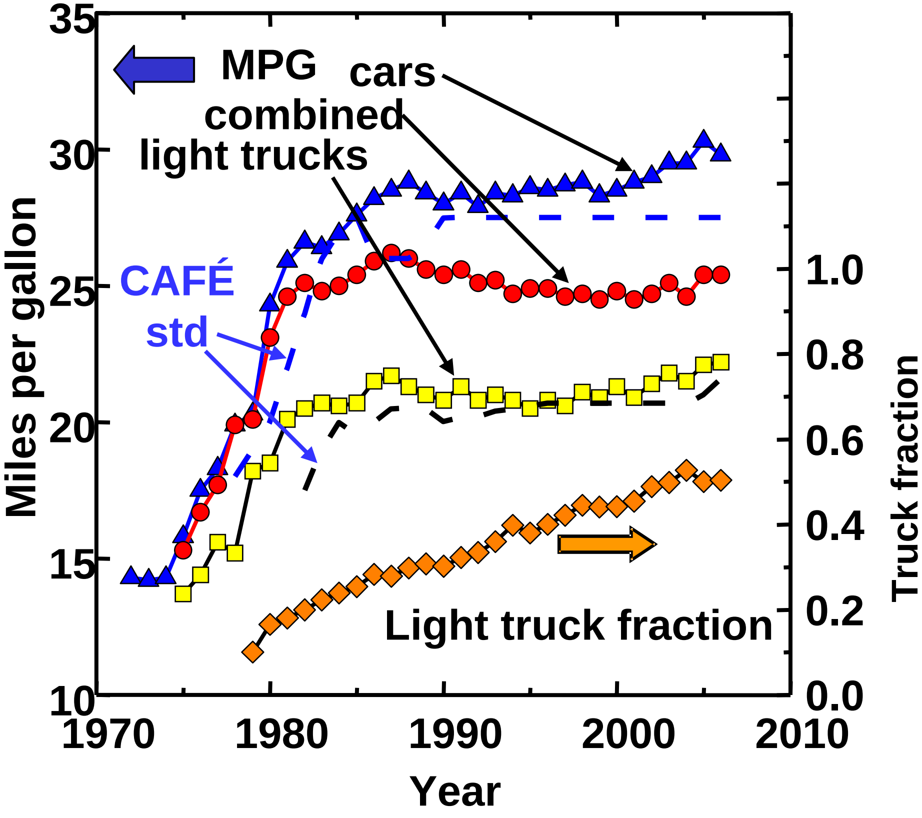
Fuel cell is NOT the technological solution

Courtesy Open Clip Art Library, http://openclipart.org

World Oil Production



US vehicles fuel economy



(Cafe target: 35 mpg average by 2020)

Progress in gas mileage !

From Time Magazine, June 2003

TRANSPORTATION EFFICIENCY

$$\text{Transportation Efficiency} = \frac{\text{"Useful people mile"}}{\text{Fuel energy}}$$

$$= \frac{\text{"Useful people mile"}}{\text{People mile}} \times \frac{\text{People mile}}{\text{Vehicle mile}} \times \frac{\text{Vehicle mile}}{\text{Road work}} \times \frac{\text{Road work}}{\text{Fuel energy}}$$

Personal efficiency

Vehicle utilization efficiency

Route, traffic pattern
Vehicle weight/speed

Engineering

Options?

- **Alternative Fuels and Power Plants ?**
- **Alternative Life Styles ?**