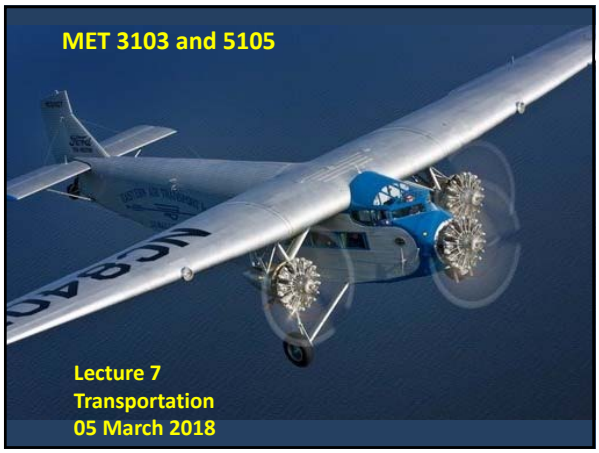



## Transportation

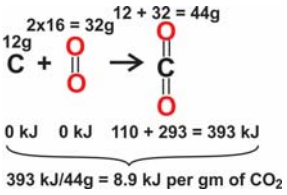
- Automobiles and airplanes are 20th Century icons of modernity
- Just as railroads and steamships were in the 19th Century
- And computers and the Internet are in the 21st Century
- The normal time from a marketable prototype to mature technology is 25-50 years
  - e.g., Wright flyer (1904) to DC3 (1936), or Boeing 707 (1958)
  - First locomotive (Salamanca, 1812) to $10^4$ km of track in UK (1850) or US Transcontinental railroad (1869)
  - Benz "Motorwagen (1886)" to Model T (1908)
- Even though automobiles are so 20th Century, everybody worldwide still wants one
- They and airplanes are nearly all powered by fossil fuel
- And emit lots of Green-House Gasses

## Units of Measurement

- Use SI units
  - Kilogram = 2.2 pounds (mass)
  - Meter = 39.4 in (length; 1 foot ~ 30 cm = 0.3 m)
  - Second (time)
- Force = mass x acceleration = kg-m/$s^2$, measured in Newtons (Nt)
  - Gravity = 9.8 m $s^{-2}$ (meters per second squared)
- Energy is force acting through a distance = Joule = kg-$m^2s^{-2}$
- Power = energy/time = Joule/second = Watt = kg-$m^2s^{-3}$
- 1 Horsepower = 745.7 W
- In chemical reactions, mass is measured in moles
  - Avogadro's number = 6.22 x $10^{23}$ atoms
  - Or the atomic weight in grams
  - C = 12 gm $CO_2$ = 12 + 2x16 = 44 gm, or $H_2O$ = 2 + 16 = 18 gm
  - Or 22.4 liters (22.4 x 0.001 $m^3$) of any gas
- We use prefixes kilo (k = 1,000) and mega (m = 1,000,000)

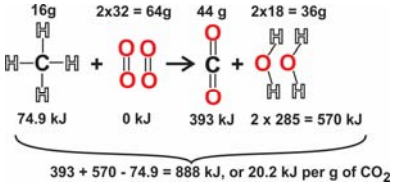
## Burning Fuel

- Most transport fuels are coal or petroleum burned in air.
- For example **coal**, which is mostly carbon
- Burn one mole of coal with one mole of oxygen to make one mole of carbon dioxide



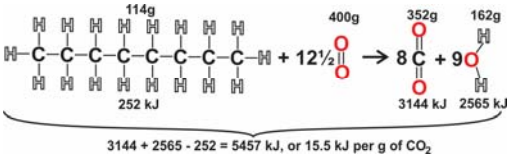

- So burning 12 gm of coal in a minute (60s) would release heat = 393000/(60x745.7) = 8.8 HP.
- Since steam engines are ~35% efficient, we would get only 3.1 HP
- Or 2300 W

## How About Natural Gas?



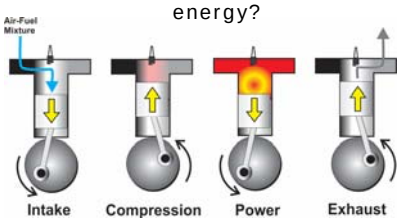

- A mole of methane weighs 16 cm, or 4 gm (¼) more than one of carbon
- But it produces more than twice as much energy
  - 888 kJ instead of 393 kJ
- Because of the heat released by making 2 moles of $H_2O$
- And it releases more than twice as much energy per gram of $CO_2$ emitted (20 vs 8.9 kJ/g)

## How About Gasoline (Octane)?




- A mole of octane weighs ~7 times as much as one of methane
- And produces about 6 times as much energy
- Because there are closer to two hydrogen atoms per carbon atom than four
- And it releases 15 kJ of heat per g $CO_2$ (20 for methane and 8.9 for pure carbon)

## How do we convert chemical energy to mechanical energy?

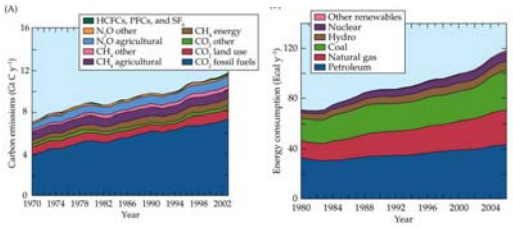



- Four-stroke, "Air-Standard Otto Cycle"
  - Intake: Draws fuel and air into cylinder
  - Compression: Heats mixture by raising pressure
  - Power: Combustion of fuel increase pressure pushing piston down
  - Exhaust: Forces burned fuel out of the cylinder
- Automobile engines convert 25-30% of the energy in fuel into useful work
- Higher compression ratios increase efficiency

## GHG Emissions and Energy Sources

**Green-House Gas Sources**

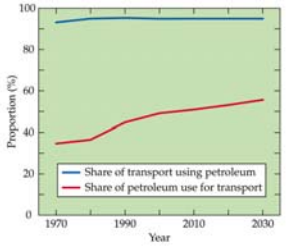
**Energy Consumption ($10^{18}$ cal/yr)**




**NOTE: 1 cal = 4.186 J or 1.163 x $10^{-3}$ W-hr**

## Petroleum and Transport

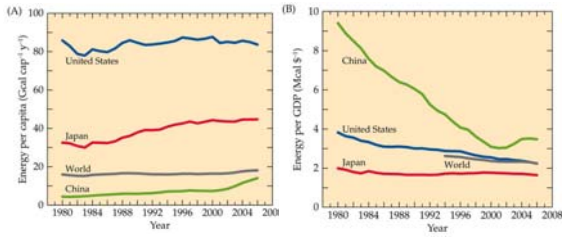
- More than 90% of 21st Century transport is fueled with petroleum
- The fraction of petroleum production used for transport will increased from 34% in 1970 to 57% by 2030.




## Representative Energy Usage by Population and GDP

**Per capita energy usage: (Gcal $yr^{-1}$ = 132.2 W; 80 Gcal $yr^{-1}$ $cap^{-1}$ = 10 kW $cap^{-1}$)**

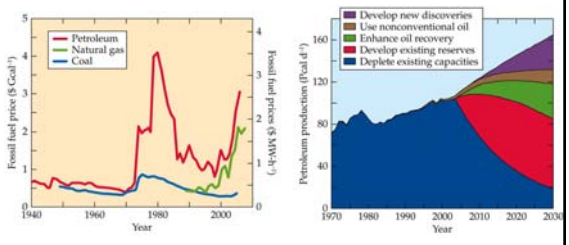
**Energy per dollar of GDP. Mcal = $4.186x10^6$ J ~ 1.1 kW h.**



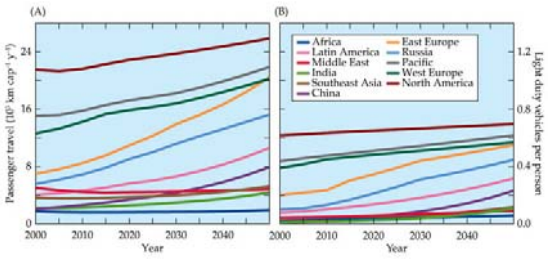

## Prices and Sources of Fuels

**Prices of Energy from Petrol. Natural Gas and Coal ($/Gcal )**

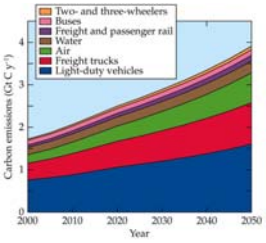
**Sources of Petroleum**



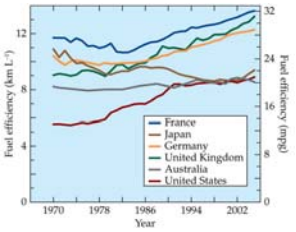

## Travel and Vehicle Ownership by Region



**Emissions by vehicle type**

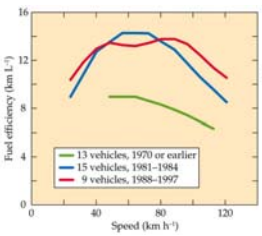



**Fuel economy in selected countries**

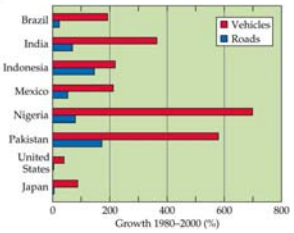



**5/8 = 62% of emissions come from cars and trucks**
**Cars, trucks, and air accounted for ¾ of transport emissions in 2000**
**Projected to be 80% in 2050**

**Effect of speed on fuel economy**




**Changes in roads and vehicle numbers by country**

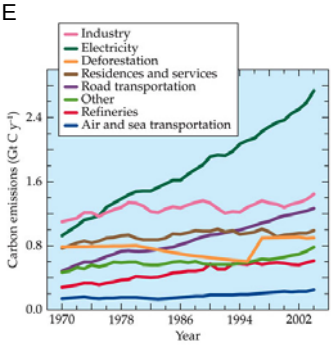



## How does it all fit together?

- People want heavier, more powerful cars
- In the developing world, people want more cars
- Fuel economy is becoming somewhat better because of better engineering
- Emissions from all modes of transportation (except busses) are increasing 2% per year
- Individuals have direct control over emissions from their cars
- Factors affecting emissions besides weight, power and numbers
  - Stop & go
  - Speed
  - Taxes
  - Gridlock, accidents & weather
  - Innovative power plants

## The BIG PICTURE

- **Worldwide, Road transportation accounts for ~10% of $CO_2$ emissions**
- **Sea and air transportation accounts for 2-3%**
- **But individuals have direct control (also in residences)**
- **Very efficient alternatives**
  - **Urban light rail**
  - **Freight rail**
  - **Containerships**
  - **Ocean liners???**
- **Note that <u>electrical generation</u> accounts for ~30% of emissions**

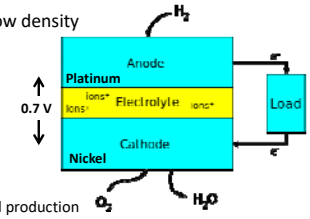



## Alternative Technologies

- Hydrogen Fuel Cell
- Gas Hybrid
- Plug-In Hybrid
- Biofuel
- Ethanol
  - Fermentation
  - Cellulosic
  - Butanol

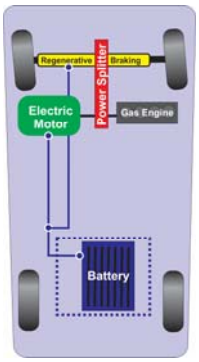
## Hydrogen Fuel Cell

- Reacts $H_2$ with $O_2$ in the presence of a catalyst to produce electric current and $H_2O$
- Hydrogen storage has low density
  - Liquid $H_2$
  - Metal hydrides
- Production of $H_2$
  - Electrolysis
  - From fossil fuel:
  - $CH_4 + H_2O \rightarrow CO + 3H_2$
- Downsides
  - Expense
  - GHG emissions from fuel production
  - Low energy density
  - Fire and explosion hazard
  - New distribution system required



## Hybrid Cars

- Have gas and electric motors
- Electric motor is also a generator
  - Powered by gas engine
  - And regenerative braking
- Gas engine is turned off except when car is moving
- Electric motor provides start up
- Gas engine runs for normal cruising
- Electric motor provides (lots of) extra torque for starting, hills, passing…
- Saves gas by not idling and by regenerative braking
- Plug-in has bigger battery for commuting and runs gas engine only when battery is low or for longer trips
- Can double fuel efficiency

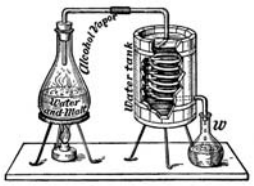



## Biofuels: Ethanol From Maize

- Capture sunlight, $CO_2$ & $H_2O$ to make Glucose stored in the grain.
- Ferment the glucose to make ethanol ($CH_3CH_2OH$) and some $CO_2$
- Distil the result to make fuel
- Burn the fuel to make energy and more $CO_2$
- Carbon neutral apart from energy inputs to growing processing and distribution

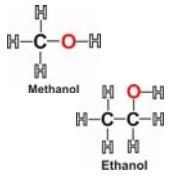
## Critique

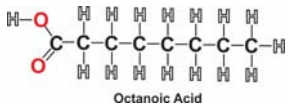
- In the US, Maize yields $10^4$ kg per hectare
- Which can produce 0.37 L of $CH_3CH_2OH$ per kg
- Or 3700 L of ethanol per hectare
- US consumes $10^{12}$ liters of crude oil per year
- Assuming one-to-one replacement of petroleum with ethanol, that 's 270,000 hectares
- Compared with 38,000 currently in maize production
- And 916,000 hectares of US land area




## Some Organic Chemistry

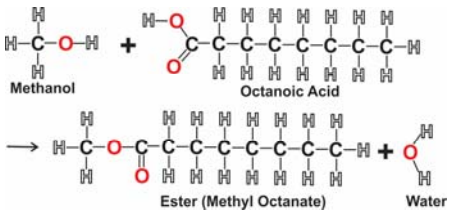
- Some fuels are organic bases (pH > 7), called alcohols:
- In addition to alcohols, there are "fatty" organic acids (pH < 7) made up of a long hydrocarbon chain with a carboxyl group (COOH) at the end.
- Vinegar, $CH_3COOH$, is an example, even though it's not all that fatty
- Octanoic acid, which is related to Octane, is another.
  - Note the COOH on the left end



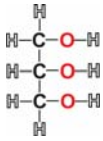

## Esters

- Alcohols and fatty acids combine to form Esters.
  - Often have pleasant smells and are used in flavoring
  - But are a problem for biofuels



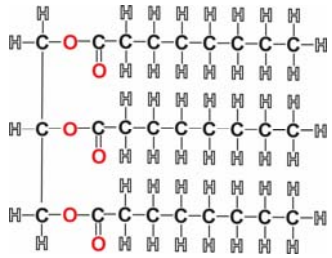

## Glycerol

- Is a 3-carbon chain with a hydroxide on each carbon.
  - Which is to say an alcohol
  - Used in cosmetics and some foods
  - A triple-threat: Alcohol that can form an ester with three fatty acids at the same time.



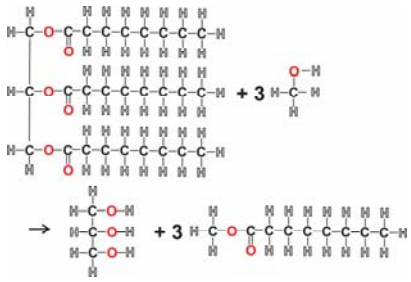
## Triglycerides

- Glycerol forms a backbone with three fatty acids attached.
- Most biologically produced fats are triglycerides
- Because they have such a large molecular weight, they do not work in internal combustion engines



## Transesterification

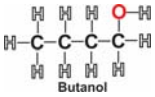
- Breaks up triglycerides into lower molecular weight oils that can be used as ***Biodiesel***



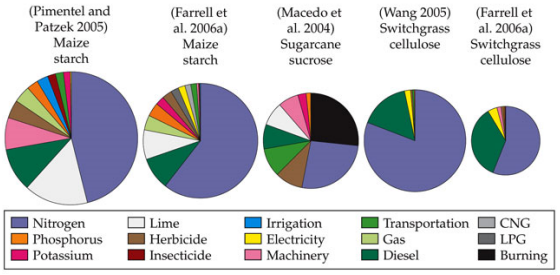
**Can be used to reclaim the energy content of waste fats (i.e., cooking oil) but purpose grown oils are much less promising**

## Switchgrass

- Switchgrass uses C4 photosynthesis
  - Tolerates drought and heat well
- Yields ~ 15,000 kg of dry biomass per hectare
  - Cellulose and lignin
- About half the energy input of Maize per hectare
- Clostridium acetobutylicum can ferment cellulose into butanol
- Process also works for waste paper, garden trash, …
- Butanol can go right into your gas tank

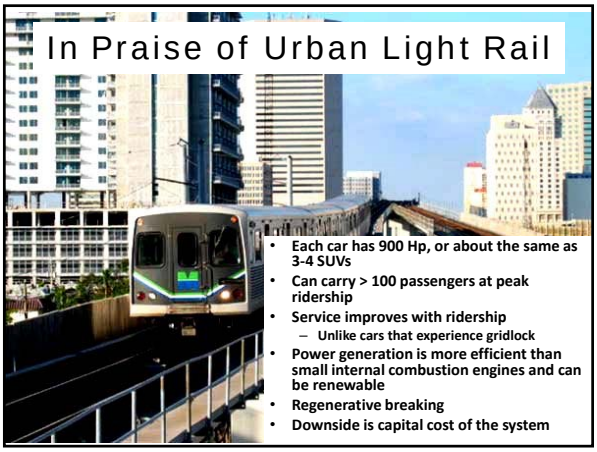



## Comparison of Energy Inputs for Biofuels




**Gram carbon equivalents per L of ethanol: 0.31,0.21,0.10,0.11,0.05**

## In Praise of Urban Light Rail



- **Each car has 900 Hp, or about the same as 3-4 SUVs**
- **Can carry > 100 passengers at peak ridership**
- **Service improves with ridership**
  - **Unlike cars that experience gridlock**
- **Power generation is more efficient than small internal combustion engines and can be renewable**
- **Regenerative breaking**
- **Downside is capital cost of the system**

## SUMMARY

- Fossil fuels account for 69% of GHG emissions
- Transportation contributes 21% globally (US:33%)
- Petroleum is principal fuel
- Methane produces 50% as much $CO_2$ per Joule as coal. Octane, etc., about 75%
- Cars are becoming more efficient, but…
- Everybody wants more, bigger & more powerful cars
- Trains & ships can be very fuel efficient
- But not airplanes
- Hybrids can double fuel efficiency
  - No idling and regenerative breaking
- Biofuels
  - Rich peoples fuel competing with poor people's food
  - Ethanol from grain
  - Biodiesel from (waste) fats
  - Switch grass and Clostridium acetobutyicum