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)

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


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 CO2 from 1990 level
- Congestion
• Reformulated Gasoline
• Methanol
• Ethanol and other bio-fuels
• Hydrogen
<table>
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<tr>
<th>Fuels</th>
<th>Density (Kg/m³)</th>
<th>LHV/mass* (MJ/Kg)</th>
<th>LHV/Vol.** (MJ/m³)</th>
<th>LHV/Vol. of Stoi.Mixture@1 atm, 300K*** (MJ/m³)</th>
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<td>Gasoline</td>
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<td>44</td>
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<td>Diesel</td>
<td>810</td>
<td>42</td>
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<td>@1 bar</td>
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<td>45</td>
<td>3.2x10¹(x)</td>
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<td>@100 bar</td>
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<td>3.2x10³</td>
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<td>LNG (180K, 30bar)</td>
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<td>1.22x10⁴</td>
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<td>8.52x10³</td>
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</table>

*Determines fuel mass to carry on vehicle
**Determines size of fuel tank
***Determines size of engine
Relative CO2 production from different fuel molecules

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?**

### Annual fuel ethanol production

- **Source:** California Energy Commission, 2006

### Fresh whole milk retail price (up to May, 08)

- **Annual average or averaged up to current month**

### Fuel Ethanol Terminal Market Price - 48-Month History

- **Spot price 5/12/08:** $2.50/gal

### U.S. All Grades Conventional Retail Gasoline Prices (Cents per Gallon)

- **May 08 spot price:** $2.50/gal
- **Retail price:** $3.80/gal

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
Ethanol from corn

- Several studies of the overall energy budget
  - $P = \text{energy used in production}$
    - feedstock production/transport + processing
  - $E = \text{Energy of the ethanol output}$
  - $\text{Return} (\%) = (E – P) / E$

- **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

* 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
• 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

- ENGINE → GENERATOR
- BATTERY
- MOTOR → DRIVETRAIN

Parallel Hybrid

- ENGINE → GENERATOR
- BATTERY
- MOTOR → DRIVETRAIN

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

66/43 mpg on Japan/US driving cycle

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

Honda Insight

80/60 mpg on Japan/US driving cycle
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)
$\delta$ is fractional improvement in mpg

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

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

(assume that interest rate is zero)
Example:
Honda Civic and Civic-Hybrid

Price premium ($\Delta$, 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 CO₂ emissions
  - Limited battery life
Sales figure for hybrid vehicles

Sales (thousands) vs. % of new light duty vehicle sale from 1999 to 2009.
What is a fuel cell?

Direct conversion of fuel/oxidant to electricity

- $2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$
- Potentially much higher efficiency than IC engines
History of Fuel Cell

• **Sir William Grove** demonstrated the first fuel cell in 1839 (H2 – O2 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

• 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

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
  - $\text{H}^+, \text{O}^{2-}$ (important difference in terms of product disposal)
Types of fuel cell (cont.)

• By electrolyte
  – Solid oxides: ~1000°C
  – Carbonates: ~600°C
  – $\text{H}_3\text{PO}_4$: ~200°C
  – Proton Exchange Membrane (PEM): ~80°C
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 infrastructure
• Hydrogen from fossil fuel is NOT an efficient energy option
• Environmental resistance for nuclear and hydroelectric options
The hydrogen problem: H₂ from reforming petroleum fuel

Note: HC to H₂/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

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

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
Fuel cell as automotive powerplant

- Current (2006) Fuel cell characteristics
  - 1A/cm², 0.5-0.7 V operating voltage
  - 0.5-0.7 W/cm² power density
  - Stack power density 0.7 kW/L
  - Platinum loading ~0.3 mg/cm²
    - 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

http://www.time.com/time/magazine/article/0,9171,1005048,00.html
Transportation Efficiency = \frac{"Useful people mile"}{Fuel energy}

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

Personal efficiency

Vehicle utilization efficiency

Route, traffic pattern
Vehicle weight/speed

Engineering
Options?

• Alternative Fuels and Power Plants?

• Alternative Life Styles?