Making the Most of Our Energy Carriers

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Outline

• Energy Situation Rant
  – Overview, Snapshot, of Energy and Mobility Situation

• Drivers and constraints for IC Engine based systems
  – Consideration of alternative fuels and powertrains

• My assessment of the fate of the IC Engine

• Fundamental needs for future power generation systems

• Closure
Demand and Supply? (Hubbert?)**

- ANWR: USGS est. 5.7–16x10^9 barrels of recoverable crude and natural gas*
  - 0.33% of mean estimate of ultimate reserves

*http://en.wikipedia.org/wiki/Arctic_Refuge_drilling_controversy
Meeting Projected Energy Demand?

• Ghawar, Abqaiq, Shaybah, Zuluf – Saudi Arabia’s four major oil fields
  – Responsible for approximately 80% of Saudi Arabia’s oil production
  – Ghawar is responsible for approximately 60% of Saudi Arabia’s production
  – Ghawar (1948), Abqaiq (1940), Shaybah (1975) and Zuluf (1965) are all using tertiary recovery techniques

Ref: Matthew Simmons, “Twilight in the Desert”
Is Supply Really an Issue?

• As demand for oil increases, its price will increase
  – More challenging reserves become economically viable – ex. Gulf of Mexico, ocean off Brazil

• Alternatives, unconventional “oil”, like tar sands become viable
  – Canada (tar sands) is currently the largest foreign importer of HC fuels to the US.

• In my opinion supply is not an issue, the real issues are carbon emission and timelines to bring new “sources” on line
  – Processing tar sands, shale oil, coal liquefaction etc., is very carbon emission intensive (tar sands ~ 3x petroleum)
  – The time required to increase the supply base of alternative, green, energy carriers is measured in multiple decades
Efficiency Gain is a Resource*

- To meet projected energy demands we will need to develop all economic energy sources
- Through 2030 the amount of energy saved through efficiency gains worldwide could be equivalent to 170 M bbl/day

* Courtesy of ExxonMobil
Is Carbon Really and Issue?

- Personally I think it is, but I also believe this is an irrelevant question
  - Geological chronologies are often couched in terms of a carbon cycle
  - The carbon cycle is determined by a balance between sources and sinks. It is possible for a perturbation to upset a balance.
  - In my mind there is no question that humans are accelerating the carbon cycle
- HC’s are the most precious energy carrier that exist
  - The petroleum used in one year took 875K years to produce
- We should do everything possible to conserve and preserve these precious resources
  - Don’t use HC energy carriers for applications where other energy carriers will also suffice
- It is also an irrelevant question because it appears likely carbon emissions will be legislated
Reducing Energy “Use” and Carbon Emissions

• We must take a holistic view
  – Wells to wheels, cradle to grave, cradle to cradle

• We must address paradigm shifts
  – Organization and structure of urban and rural living, commuting, working, recreation, etc.

• Energy intensity of our life styles will become a controlling metric
Predicted Fuel Consumption and Greenhouse Gas Emissions for Different Powerplants

- HEV and PHEV offer best potential for minimizing CO2 in the near and mid term time frames
  - CO2 emission from PHEV will depend on the electricity generating mix
- Not shown are costs of the technologies
  - Turbo SI and Diesel are most cost competitive

On The road in 2035
http://web.mit.edu/sloan-auto-lab/research/beforeh2/otr2035/
Regardless of the Evolving Paradigm

• Power generation will still be a necessary aspect of our existence
• Our power generation systems will be constrained by:
  – Energy “use”
  – Emission impact

\{ \text{Ecological Footprint} \}
Reducing Carbon Emissions from our Power Generation Systems?

• Using power generation systems with non carbon energy carriers
  – Electric (batteries)
  – Hydrogen
    • Of course one must consider carbon emissions from energy source to the vehicle

• Recycle or sequester the carbon
  – Carbon sequestration
  – Bio-fuels

• Reduced fuel consumption for IC engines
  – Must also meet regulated emission standards
Electric Propulsion

Battery Technology
Battery Technology – Two Centuries Of Progress

1801 Volta
Zn-Cu

1839
Fuel Cell
Pb Battery

1859
Ni-Cd
Li-Metal

1899
Ni-MH
Li-Polymer

1973
Li-Metal

1975

1979

1990
Sony
Li-Ion

2000
Bellcore
Plastic
Li-Ion

Battery development generally proceeds from small sizes to larger sizes as the technology matures.

Source: Tarascon
Energy Content (continued)

Energy Density Comparison

- Gasoline & Diesel
- FreedomCAR 2010 H2 storage goal
- FreedomCAR 2015 H2 storage goal
- Current H2 storage capabilities

H₂ information source: 1st NRC FreedomCAR Fuel Partnership Report, 2005
Comments

- Batteries offer the potential to use electrons as an energy carrier from a portfolio of alternative energy sources
  - Currently ~50% of the electricity generated in the US is generated from coal
- Energy density of batteries will be significantly less than HC energy carriers
  - "The maximum theoretical potential of advanced lithium-ion batteries that haven't yet been demonstrated to work is still only about 6 percent of crude oil." - *The Limits of Energy Storage Technology, Kurt Zenz House, The Bulletin of Atomic Scientist, 20 January, 2009*
- Fuel cells will have to compete with battery electric vehicles
- There will be applications where it will be very difficult to displace combustion engines with HC fuels
Hybridization Offers Many Opportunities

• Hybridization may offer opportunities to load level or maintain engine “sweet spot” operation
  – Parallel and/or series hybrids
  – Electric or Hydraulic
    • Electric – applications where energy storage for longer times is beneficial
    • Hydraulic – applications where large power flows, with relative short storage times are required

• Optimization of a hybridized systems is dependent on the duty cycle
  – For many companies the duty cycle is viewed as proprietary information
Internal Combustion Engines

with

HC, or HCO Fuels
Bio-fuels?

- Bio fuels are oxygenated HC’s
  - They will not be as high in specific energy or energy density as gasoline or diesel. But they will be better than $\text{H}_2$ or batteries

- With Bio fuels you are “recycling” the carbon emissions

- Bio fuels are a complicated topic
  - Need to do accurate accounting of all growing, harvesting and processing energy and emissions
    - Water consumption, etc…
  - It appears that Bio fuels can be a contributor to the fuel pool, but are not THE solution
  - In terms of contribution, cellulosic bio-fuel is needed
Bio-Fuels are Unconcentrated Solar Energy Storage

• To displace 30% of personal mobility fuel:
  – ~2000 m²/car/year, or 460 x10⁹ m² of land for the US fleet
    • (Assumed 31 mpg, 30 miles/day)
  – ~6% of continental US surface area
Well-to-Wheels Energy Footprint

Conventional Gasoline

Andrew Kaufman, UW Undergraduate, Independent Study using ANL GREET

Low Sulfur Diesel

E85 Herbaceous Biomass**

**Herbaceous Biomass consists of organic plant material such as corn stover, wheat straw and switch grass
Let’s Talk About Engines/Power Systems
System view of an Application’s Energy Flow

Modern Truck Fuel Economy Range
Typical 3.5 mpg urban, stop/go
Typical 6.7 mpg interstate
65,000-80,000# gross weight

Aerodynamic Losses
Urban = 4-10%
Interstate = 15-22%

Engine Losses
Urban = 58-60%
Interstate = 58-59%

Inertia/Braking
Urban = 15-20%
Interstate = 0-2%

Rolling Resistance
Urban = 8-12%
Interstate = 13-16%

Drivetrain
Urban = 5-6%
Interstate = 2-4%

Auxiliary Loads
Urban = 7-8%
Interstate = 2.5-5%

Class 8 truck energy audit from 21 CTP Roadmap, 2000
Updated Oct 2008
Partitioning of the Fuel Energy

- HC energy carriers are precious
  - Theoretical efficiency is 100%
- Availability partitioning diagrams show where the losses are
- Combustion irreversibilities are very hard to reduce
  - Would require a completely different engine

Weissman, Walt, ExxonMobil, presented at UW-ERC, 9 June 2005
Availability Considerations in Combustion

- Engine Responds to a Fuels Availability
  - Minimum availability destruction occurs at stoichiometric combustion
- Maximum efficiency occurs for lean combustion
  - No attempt to recover availability in the exhaust
- Are the avenues to reduce the availability destruction that occurs during combustion?

\[ W_{\text{max, useful}} = -\Delta G \]
\[ W_{\text{max, useful}} = -(H_{\text{prod}} - H_{\text{react}}) + T_o (S_{\text{prod}} - S_{\text{react}}) \]
\[ W_{\text{max, useful}} = Q_{HV} + T_o (S_{\text{prod}} - S_{\text{react}}) \]

*Edo and Foster, VI International Symposium on Alcohol Fuels Technology, Ottawa Canada, 1984*
Trying to Reduce Combustion Irreversibilities

- **Simulated Constant Temp. Combustion**
  - Work extraction rate matched combustion rate of fuel introduction/combustion rate matched work extraction rate
  - Base case – expansion stops when combustion stops
    - Vertical line is condition where P=1 atm at EOC
  - Overexpanded – expansion/compression continues until the gases in the cylinder are at atmospheric pressure

- **Constant temp. combustion does not reduce comb. irrev.**

Druecke, et al., Central States Combustion Institute, Chicago, IL, March 2006
Engine Efficiency and/ vs. Emissions

- Fuel economy will be “king”
- Emissions will still be a constraint
  - With increasing world population it is likely that emission regulations will continue to become more stringent
    - More applications will be regulated
    - New aspects of regulation will be introduced
      - Particulate number
      - More comprehensive tests
    - OBD will add new challenges
Powertrain Integration and Total System Optimization

- The aftertreatment system, which is passive, will dictate the engine operating conditions.
- Engine needs to supply the exhaust thermodynamic state and composition that is needed for optimum aftertreatment performance at that instant.
- Detailed fundamental understanding of each sub-system will be required.
Historical Perspective of HD Brake Thermal Efficiency

HECC DoE Effort
- Advanced Mixed Mode Combustion
- Air Handling (Air on Demand - Electronically Assisted)
- HPCR Fuel System Technology
- Sensors / Controls Development

Brake Thermal Efficiency (%)
Combustion Optimization and New Combustion Regimes

Task 1: Fundamental understanding of LTC-D and advanced model development

Task 2: Experimental investigation of combustion control concepts

Task 3: Application of models for Optimization of combustion & emissions

Task 4: Impact of heat transfer and spray impingement on LTC-D combustion

Task 5: Transient engine control with mixed-mode combustion

Ford DIATA engine http://www.tev.com/
Low-Temperature Combustion (LTC)

- Critical Issues:
  - Practical “windows” can be identified:
    - $T < 2100 \text{ K}$ to keep NOx from forming
    - $T > 1500 \text{ K}$ to generate sufficient OH to complete oxidation of CO and HC
  - Exhaust temperature are low with LTC
    - Catalytic clean up of the exhaust may be difficult
  - The soot and NOx islands were determined by static calculations of, $T = 1.0 \text{ ms}$, $P = 6 \text{ MPa}$ and $EGR = 0\%$. In reality they move!

Concept was originally proposed by Kamimoto, SAE 880423
LTC Single Injection Research

From SAE 2007-01-0193 and SNL Research Overview

- Carbon Monoxide Related Concepts
  - Liquid fuel in squish region
  - Vaporized fuel at SOC
  - Bulk fluid mixing
  - Spray targeting
  - "Sweet Spot" injection targeting
SMPS Size Distribution

Concentration [dN/dlogDp] vs. Diameter [nm]

Case 1: Conv. High Load
Case 2: Conv. Med. Load
Case 3: LTC High Inj. Pressure
Case 4: LTC Low Inj. Pressure
# Size and Mass Statistics

<table>
<thead>
<tr>
<th>Case</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Number Concentration [#/cc] xE9</td>
<td>4.05</td>
<td>2.42</td>
<td>3.12</td>
<td>5.08</td>
</tr>
<tr>
<td>Geometric Mean Particle Diameter [nm]</td>
<td>120</td>
<td>70.3</td>
<td>38.8</td>
<td>64.6</td>
</tr>
<tr>
<td>Mode [nm]</td>
<td>126</td>
<td>76</td>
<td>40</td>
<td>69</td>
</tr>
<tr>
<td>Teflon Filter Mass [g/kg_fuel]</td>
<td>2.4</td>
<td>0.39</td>
<td>0.08</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Europe is implementing a number standard, $6 \times 10^{11}$ particle/km, CARB proposes this for LEVIII

<table>
<thead>
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<td>4</td>
<td>LTC Low Inj. Pressure</td>
</tr>
</tbody>
</table>
Filter Analysis

Color difference between PM from Conventional and LTC diesel combustion
Unconventional Fuels in Unconventional Engines?

• “Gasoline, The Best Fuel for Diesel Engines” ERC Symposium 2007, Kalghatgi et al. (SAE 2007-01-0006)

• Operating a Heavy-Duty Direct-Injection Compression-Ignition Engine with Gasoline for Low Emissions (SAE 2009-01-1442)
Summary

• HC, or HCO, fuels will continue to be the energy carrier for mobility systems for decades to come.
• IC Engines, including hybrids, will be viable powerplant for decades to come
• To simultaneously minimize carbon emissions and regulated “pollutants” each individual component of the system will need to be thoroughly, and fundamentally understood, and optimized in a system configuration.
• Thorough and fundamental understanding is lacking in many of the system components being considered for 2010 and beyond.
• Experimental investigations, coupled with detailed and system modeling will be critical aspects of the path forward.
Thank you

• Questions?

“Okay – it’s agreed; we announce – ‘to do nothing is not an option!’ then we wait and see how things pan out…”

Figure 1.11. Reproduced by kind permission of PRIVATE EYE / Paul Lowe www.private-eye.co.uk.

From: Sustainable Energy - without the hot air