Fuels of the Future for Cars and Trucks

Dr. James J. Eberhardt
Energy Efficiency and Renewable Energy
U.S. Department of Energy

2002 Diesel Engine Emissions Reduction (DEER) Workshop
San Diego, California
August 25 - 29, 2002
What Energy Source Will Power Engines of the Future?

- Presently we know of no energy source which can substitute for liquid hydrocarbon fuels.

- No other fuels:
  - Are so abundant
  - Have such a high energy density
  - Have such a high power density
  - Store energy so efficiently and conveniently
  - Release their stored energy so readily (rapid oxidation/combustion)
  - Have existing infrastructure
  - Are so easily transported
Currently, we see only 2 potential non-carbon based energy carriers that have the requisite volume needed to replace petroleum fuels

- Hydrogen
- Electricity
Energy Density of Fuels

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Energy Density (Thousand Btu per ft³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel Fuel</td>
<td>1058</td>
</tr>
<tr>
<td>F-T Diesel</td>
<td>990</td>
</tr>
<tr>
<td>Biorenewable Diesel</td>
<td>950</td>
</tr>
<tr>
<td>Gasoline</td>
<td>922</td>
</tr>
<tr>
<td>Propane</td>
<td>683</td>
</tr>
<tr>
<td>LNG</td>
<td>635</td>
</tr>
<tr>
<td>Ethanol</td>
<td>594</td>
</tr>
<tr>
<td>Methanol</td>
<td>488</td>
</tr>
<tr>
<td>Liquid H₂ (@ 3626 psi)</td>
<td>270</td>
</tr>
<tr>
<td>Compressed Hydrogen (NiMH)</td>
<td>266</td>
</tr>
<tr>
<td>Battery</td>
<td>68</td>
</tr>
<tr>
<td>NiMH Battery</td>
<td>16</td>
</tr>
</tbody>
</table>
Energy Density of Fuels
Normalized to Diesel Fuel

- Diesel Fuel: 100.0%
- F-T Diesel: 93.6%
- Biorenewable Diesel: 89.8%
- Gasoline: 87.2%
- Propane: 64.6%
- LNG: 60.0%
- Ethanol: 56.2%
- Methanol: 46.1%
- Liquid H₂ (@ 3626 psi): 25.5%
- CNG (@ 3626 psi): 25.1%
- Compressed Hydrogen (@ 3626 psi): 6.4%
- NiMH Battery: 1.3%
Comparison of Energy Conversion Efficiencies

- Fuel Cell-Stored Hydrogen
- Fuel Cell-Methanol Reformer
- Homogeneous Charge Compression Ignition*
- Heavy Duty DI -Diesel Engine
- Compression-Ignition Direct-Injection ICE
- Gas Turbine
- Gasoline Direct Injection
- Conventional Spark Ignition ICE

Peak Thermal Efficiency (%)

- Today's Capability

* HCCI research focus: operate well across the load-speed map and extend the operating range to higher loads
Vehicle Range Limitation - Challenge To Be Overcome By Alternatives

Comparison of Miles Driven
(Same Volume of On-Board Fuel)

- Diesel Engine-Conv. Diesel Fuel
- Diesel Engine-F-T Diesel
- Fuel Cell - Gasoline
- Direct Injection Engine- Gasoline
- Adv. NG Engine-CNG (3,600 psi)
- Fuel Cell- Hydrogen (3,600 psi)

Today's Capability
The Defining Characteristic: Car versus Truck

Car: A vehicle designed for a payload (people) which **never** exceeds its unloaded weight

Heavy Truck: A vehicle designed for a payload which **routinely** exceeds its unloaded weight
## Truck Classification (by Gross Vehicle Weight)

<table>
<thead>
<tr>
<th>Class</th>
<th>Weight Range</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6,000 lbs. &amp; Less</td>
<td>Multi-purpose, Mini-pick-up, Full-size pick-up</td>
</tr>
<tr>
<td>2</td>
<td>6,001-10,000 lbs.</td>
<td>Minivan, Utility Van, Crew compartment pick-up</td>
</tr>
<tr>
<td>3</td>
<td>10,001-14,000 lbs.</td>
<td>Walk-in, City Delivery, Mini-bus</td>
</tr>
<tr>
<td>4</td>
<td>14,001-16,000 lbs.</td>
<td>Conventional Van, Large Walk-in, City Delivery, Landscape/Utility</td>
</tr>
<tr>
<td>5</td>
<td>16,001-19,500 lbs.</td>
<td>Bucket, City Delivery, Rack, Single Axle Van, Beverage</td>
</tr>
<tr>
<td>6</td>
<td>19,501-26,000 lbs.</td>
<td>School Bus, Stake Body</td>
</tr>
<tr>
<td>7</td>
<td>26,001-33,000 lbs.</td>
<td>Home Fuel, Refuse, City Transit Bus, Medium Conventional</td>
</tr>
<tr>
<td>8</td>
<td>33,001 lbs. &amp; Over</td>
<td>Dump, Cement, Heavy Conventional, COE Sleeper</td>
</tr>
</tbody>
</table>
## Cars and Light-Duty Trucks vs. Heavy-Duty Trucks

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Common GVW (lbs)</th>
<th>Unloaded Weight (lbs)</th>
<th>Payload (lbs)</th>
<th>Payload to Unloaded Weight Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Family Sedan – 5 passengers</td>
<td>3,400</td>
<td>~ 3,100</td>
<td>~ 1,000</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(5 x 200 lb)</td>
<td></td>
</tr>
<tr>
<td>Light Truck</td>
<td>5,150</td>
<td>4,039</td>
<td>1,111</td>
<td>28</td>
</tr>
<tr>
<td>Class 2b Truck</td>
<td>8,600</td>
<td>4,962</td>
<td>3,638</td>
<td>73</td>
</tr>
<tr>
<td>Class 3 Truck</td>
<td>11,400</td>
<td>5,845</td>
<td>5,600</td>
<td>96</td>
</tr>
<tr>
<td>Class 4 Truck</td>
<td>15,000</td>
<td>6,395</td>
<td>8,605</td>
<td>135</td>
</tr>
<tr>
<td>3-axle single unit truck</td>
<td>50,000 to 65,000</td>
<td>~ 22,600</td>
<td>27,400 to 42,400</td>
<td>121 to 188</td>
</tr>
<tr>
<td>4-axle single unit truck</td>
<td>62,000 to 70,000</td>
<td>~ 26,400</td>
<td>35,600 to 43,600</td>
<td>135 to 165</td>
</tr>
<tr>
<td>5-axle tractor semi-trailer</td>
<td>80,000 to 99,000</td>
<td>~ 30,500</td>
<td>49,500 to 68,500</td>
<td>162 to 225</td>
</tr>
</tbody>
</table>
Volume of Fuel Needed for Equivalent Range
(1,000 mile range)

Diesel Fueled – Two (one on each side) 84 gallon tanks (23 ft³)

Loss of revenue cargo space!

Fuel Cell/Hydrogen Fueled – Two 1,180 gallon tanks (316 ft³) at 3,600 psi (Each tank approximately: L = 150”, D = 48”)

Space and Weight Estimates for HV Batteries

Cargo Space in trailer is typically 6,080 ft$^3$
Front Axle Capacity is 12,000 lb, Rear Axle Capacity is 38,000 lb

Assumptions:
- Truck: 310 HP, 6 mpg fuel economy, 45% average engine thermal efficiency

<table>
<thead>
<tr>
<th>Performance</th>
<th>Battery Space</th>
<th>Battery Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(ft$^3$)</td>
<td>(% of cargo)</td>
</tr>
<tr>
<td>Range - 500 miles</td>
<td>358</td>
<td>5.9%</td>
</tr>
</tbody>
</table>

LMP Batteries
A Compact and Portable Way to Store Hydrogen for the Fuel Cell Car?

- Sodium borohydride (a salt) is dissolved in water where it stays until gaseous hydrogen is needed.
- When H₂ is needed, the solution is pumped over a catalyst.
- The H₂ gas comes out and leaves behind sodium borate (another salt) which remains dissolved in water and goes to the spent fuel tank.

\[
\text{NaBH}_4 + 2\text{H}_2\text{O} \rightarrow 4\text{H}_2 + \text{NaBO}_2 \text{ catalyst}
\]

- We have to carry 73.8kg for every 8kg of Hydrogen which is about 11% by weight or <50% that of methane, CH₄.
Sodium borohydride is derived from borax, which is abundant and widely available.

Sodium borate is a common, non-toxic household item used in detergents.

Sodium borate can be recycled into new sodium borohydride.

To recycle sodium borate into new sodium borohydride requires a reduction reaction in a kiln at 900°C under highly corrosive environment.

Coke or methane (CH₄) is needed:

\[ \text{CH}_4 + \text{NaBO}_2 \xrightarrow{900\,^\circ\text{C}} \text{NaBH}_4 + \text{CO}_2 \]

It takes more energy to make sodium borohydride than the energy released (or recovered) in the fuel cell.
Volume of Fuel Needed for Equivalent Range
(1,000 mile range)

Diesel Fueled – Two (one on each side) 84 gallon tanks (23 ft³)


Loss of revenue cargo space!
To Enable Replacement of Petroleum as Primary Energy Carrier for Ground Transportation

Fuel Cells for Heavy Vehicle Propulsion: Practical Considerations

- Hydrocarbon fuels need to be reformed on board the vehicle to produce $\text{H}_2$
- Furthermore, water gas shift is necessary to convert the energy content in the carbon-carbon bonds to $\text{H}_2$
- Powertrain hybridization may be required for heavy vehicle acceleration
Energy Embodied in Carbon-Carbon Bonds Increases with Hydrocarbon Molecular Weight

\[ C_nH_{2n+2} + \frac{n}{2}O_2 \rightarrow nCO + (n+1)H_2 - \) H

<table>
<thead>
<tr>
<th>Percent of Energy in Reaction Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>70</td>
</tr>
<tr>
<td>65</td>
</tr>
<tr>
<td>60</td>
</tr>
<tr>
<td>55</td>
</tr>
</tbody>
</table>

Red: Carbon Monoxide  Blue: Hydrogen
On-Board Reforming of Hydrocarbons to Produce Hydrogen for the Fuel Cell

Partial oxidation of a hydrocarbon into CO and H₂

\[ C_nH_{2n+2} + \frac{n}{2}O_2 \xrightarrow{POx} nCO + (n+1)H_2 - \) H \]

Water-gas shift reaction of CO to produce more H₂ (also produces CO₂)

\[ CO + H_2O \xrightarrow{Steam} H \rightarrow H_2 + CO_2 \]
To Enable Replacement of Petroleum as Primary Energy Carrier for Ground Transportation

Research Breakthroughs Are Needed

- Major technological breakthroughs are needed if hydrogen fuel cells are to displace the diesel engine
  - Electrolytic/water “splitting” hydrogen production (renewable, nuclear)
  - Low pressure on-board gaseous fuel storage OR on board highly efficient hydrocarbon fuel reformer
  - Greatly reduced catalyst loading in fuel stack/reformer (cost reduction)

- Major technological breakthroughs are needed if electrical energy is to displace the diesel engine
  - Electrical generation from non-fossil resources (renewable, nuclear)
  - On board high energy/high power density electric storage
DOE’s FreedomCAR and Truck Partnerships

“While FreedomCAR is concerned with light-duty vehicles, we are also working with trucking industry partners on a revitalized 21st Century Truck Initiative.”

“Unlike FreedomCAR, which is focused on hydrogen powered fuel cells, this 21st Century Truck Partnership will center on advanced combustion engines and heavy hybrid drives that can use renewable fuels.”

“The new technologies in these engines and drives could, in effect, result in heavy truck transportation using dramatically less diesel fuels and throwing off virtually no emissions of NOx or soot.”

- Remarks of Energy Secretary Spencer Abraham at the 13th Annual Energy Efficiency Forum, National Press Club, June 12, 2002
Heavy-Duty Diesel – Increasingly Dominant Engine for Heavy Vehicles

- Improved fuel quality
- Combustion technology
  - DI rate shaping/electronic controls
  - HCCI (part load)
- Aftertreatment technology
- Hybridization
Future Liquid Fuels Strategy?

High-efficiency clean diesel-cycle engines utilizing compression ignitable clean fuels/blends derived from diverse feedstocks

Multiple Alternative Feedstocks

- Coal
- Biomass
- Natural Gas
- Petroleum

Clean Diesel Fuels/Blends

- Common Diesel Fuel Specification
- Uses Existing Infrastructure

Advanced High-Efficiency Clean Diesel Engine Technologies

Efficient Low Emission Heavy Vehicles

- Heavy Truck
- Construction/ Farming Vehicles
- Locomotive

In-cylinder Processes

Fuel Quality

Exhaust Treatment

Synthesis gas route to:

Liquid Fuels

Conventional petroleum refining
Fischer-Tropsch Fuel Production

New Fischer-Tropsch production with partial oxidation and Cobalt-based catalysts reduces CO₂ formation

New Syngas Production

catalytic partial oxidation  \[ \text{CH}_4 + \frac{1}{2} \text{O}_2 \rightarrow \text{CO} + 2\text{H}_2 + \text{heat} \]
steam reforming  \[ \text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{Co-based} \rightarrow 2\text{H}_2 + \text{CO} \]

Fischer-Tropsch Reaction
\[ \text{CO} + \text{H}_2 \rightarrow \text{Co catalyst} \rightarrow (\text{H}_2\text{C-})_n + \text{H}_2\text{O}_{(g)} + \text{heat} \]
Fuels for the Next 10 Years

- Low sulfur diesel fuel (15 ppm)
- Low sulfur gasoline (30 ppm)
- Niche fuels in heavy-duty market
  - Natural Gas (as gas - CNG) – local delivery fleet vehicles
  - LNG (long haul fleet vehicles)
  - Biodiesel (B20) (long haul vehicles, marine applications)
- Natural gas derived liquids
  - Fischer Tropsch (blendstock for petroleum Diesel fuel)
- Ethanol as replacement oxygenate for MTBE in gasoline

Dominant
Summary

What Will Be the Fuels of the Future?

- **In the Near Term**
  - Low sulfur gasoline and low sulfur diesel

- **In the Mid to Long Term**
  - Hydrogen from safe on-board storage appears promising for light-duty vehicles (FreedomCAR)
  - Breakthroughs are necessary in the economical production and intermediate storage (e.g., CH$_3$OH, NaBH$_4$) of hydrogen for light-duty vehicles

- **For the Foreseeable Future (Next 10 - 25 years)?**
  - With no alternative yet identified, it appears that hydrocarbon-based fuels (from a variety of feedstocks) will be the future fuels for heavy-duty vehicles