Engine Maturity, Efficiency, and Potential Improvements

John W. Fairbanks
Office of FreedomCAR and Vehicle Technologies
US Department of Energy, Washington, D.C.

Diesel Engine Emission Reduction Conference
Coronado, California
August 30, 2004
- Transportation engine development chronology
- Diesel engine development
- Transportation applications
- Current fuel situation
- Diesel potential
Diesel Engines

Are they old and mature (i.e. fully-developed technology)?
Transportation Entering The 19th Century

- **Stage coach**
  - 8 Passengers
  - 4 Horsepower (quadrupeds)
  - One Shilling (25¢) for 4 miles

- **Bio-mass derived fuel**
  - Minimally processed

- **Emissions**
  - Bovine methane
  - Agglomeration of macro particles
    - Minimally airborne
    - Recyclable

- **Infrastructure already in place**
XIV. On the Application of Hydrogen Gas to produce a moving Power in Machinery; with a Description of an Engine which is moved by the Pressure of the Atmosphere upon a Vacuum caused by Explosions of Hydrogen Gas and Atmospheric Air.

BY THE REV. W. CECIL, M. A.

FELLOW OF MAGDALEN COLLEGE,
AND OF THE CAMBRIDGE PHILOSOPHICAL SOCIETY.

[Read Nov. 27, 1820.]
1820, by Rev. Cecil

- Based on hydrogen gas mixed with atmospheric air
  - Ignition by flame
  - Density of exploded gas $\approx \frac{1}{6}$ of atmospheric pressure
  - Atmospheric pressure provides moving force

- Complex, impractical.
- Inspiration for Rube Goldberg.
Lenoir’s “Hippomobile” Gas Engine (1860)

- Patented by Jean Joseph Etienne Lenoir in 1860
- First successful internal combustion engine
- Two-stroke gas driven engine
Lenoir's “Hippomobile” (1860)

- Built in 1860 by Lenoir
- 1-Cylinder, horizontal arrangement
- Powered by hydrogen
  - Generated via the electrolysis of water
First Functional Fuel Cell

- 1839, by Sir William Grove
- Reaction of sulfuric acid solution in lower reservoirs produces water and electricity
- Water in upper reservoir electrolyzed, producing hydrogen and oxygen
  - Upper solution used as a voltmeter
First Fuel Cell Vehicle

- 1966 Fuel Cell Van ("Electrovan")
- 7,000 pounds
- Fuel
  - Liquid Hydrogen
  - Liquid Oxygen
- Concepts, prototypes, and a limited number in demonstration fleets
- Today’s fuel cell powertrain cost ~7 times the price of production ICE engine powertrain

GM’s Hy-Wire
Fuel Cell Concept Car
Nicolaus Otto’s Four-Stroke Cycle and Engine

- 1876 - four stroke engine cycle
  - 3 hp
  - 108/min
- One combustion cycle: four-strokes
  - Intake
  - Compression
  - Power
  - Exhaust
First Gasoline-Powered Automobile

- Effective 4 stroke internal combustion gasoline engine invented (1876)
- First gasoline engine used in an automobile
- Built in 1886 by Gottlieb Daimler using Otto’s cycle
Rudolph Diesel’s Patent and the First Diesel Engine (1893)
World’s first diesel passenger car
Introduced by Mercedes-Benz in 1936
Diesel engines are not the oldest transportation vehicle engine
Sources of Increases in Diesel Efficiency

- Improved science to the art of engine development
- Sophisticated design tools using computer models
  - Enhanced understanding of engine stresses and temperatures
  - Laser diagnostics in combustion
  - Computer aided manufacturing
  - Rapid prototyping
- Improved manufacturing and quality control
  - Tighter tolerances
  - Improved castings
- Better materials and coatings
- Fuel injection equipment (computer-controlled)
- Increased turbocharger efficiency
  - Variable nozzle geometry
- Emissions aftertreatment
- Displaces steam engines
  - Deep water commercial cargo & cruise ships
    - QE II – built in mid 1950s
      - Steam turbine propulsion: 21 ft/gal fuel
    - Replaced with diesel propulsion & ship’s service generators in 1987
      - Diesel engine propulsion: 39 ft/gal fuel
      - Reduced vibrations
  - Inland marine tugs, ferries, fishing boats, pleasure boats
Rapid Transition Steam to Diesel Railroads Starting in 1930s

- Non-electrified Railroads
  - 42% improved efficiency
  - Significant emissions reduction
  - Dramatically improved working conditions
Diesel, the Only Practical Commercial Engine On- and Off- Highway

- Long-haul tractor-trailer trucks are almost exclusively diesel
- Emissions have been reduced by 88% in the last 12 years

- Off-road, diesel fuels nearly 100 percent of the off-road equipment used in construction
- In less than a decade (1996-2003)
  - PM reduced by 63%
  - NOx reduced by 28%
Applications Displacing Gasoline Engines

- Off-highway: construction, garbage, cement mixer, agricultural machinery, and mining
  - 99% diesel
- Class 7 and 8 heavy-duty trucks
  - 1.6 million trucks (99% diesel)
  - Carries 72% of all goods (dollar value)
  - No serious challenge to diesel on the horizon
- Personal vehicles
  - Europe: ~ 50%
  - North America: ~1%
2005 Mercedes Benz and VW: Diesels ~4% of North American Sales
Light-Duty Trucks: Fuel Economy Opportunity For Diesels
## Performance of Diesel Engines Developed at Cummins with DOE Support

<table>
<thead>
<tr>
<th></th>
<th>City mpg</th>
<th>Highway mpg</th>
<th>Combined mpg</th>
<th>Combined gal/mi</th>
<th>CO₂ Reduction</th>
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<tbody>
<tr>
<td><strong>Dodge Durango</strong></td>
<td></td>
<td></td>
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<tr>
<td>.Gasoline</td>
<td>12</td>
<td>17</td>
<td>13.8</td>
<td>0.072</td>
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<tr>
<td>.Diesel</td>
<td>20.3</td>
<td>25.0</td>
<td>22.1</td>
<td>0.045</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>+60% Better</td>
<td>37% Reduced</td>
<td>27%</td>
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<tr>
<td><strong>Dodge Ram 1500</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>.Gasoline</td>
<td>12</td>
<td>16</td>
<td>13.5</td>
<td>0.074</td>
<td>--</td>
</tr>
<tr>
<td>.Diesel</td>
<td>19.8</td>
<td>24.6</td>
<td>21.7</td>
<td>0.046</td>
<td>--</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>+61% Better</td>
<td>38% Reduced</td>
<td>28%</td>
</tr>
</tbody>
</table>
“The state wants to cut vehicles’ output of carbon dioxide by 30 percent over the next decade, limiting a major greenhouse gas through to contribute to global warming.”
Climate Shift Threatens California

Two GHG Emission Scenarios

- Fossil fuel use continuing at its present pace
  - Summertime high temperatures could increase by 15°F in some inland cities
- Considerable use of wind and solar power
  - Could push temperatures 4-6 °F

“...rising temperatures could lead to a sevenfold increase in heat-related deaths in Los Angeles and imperil the state’s wine and dairy industry.”

*Proceedings of the National Academy of Sciences, (August 16 2004)*
Global Climate Effect on the Maine Lobster Industry

Not a lot of lobster

Global warming blamed

By Jeff Conn, The Washington Times

FRIENDSHIP, Maine—A summer visit to Maine's coast, but especially from a moored Brandywine, a hand-built wooden boat, with the Lubec Narrows below and Acadia's Otter Cliff ahead, is a treat for one who enjoys lobstering and seafood cooking. The Brandywine, a 42-foot wooden fishing boat, is a favorite among lobster fishermen who enjoy the peace and quiet of the Lubec Narrows.

Maine's lobstermen have been boosting their annual catch for almost 15 years. Their 62.7 million pounds in 2004 are a record—up from the typical catch during the 1990s. That's more than 100 million worth of lobster and by far the dominant share of the New England lobster industry.

Maine's lobsters have been subject to challenges from a warming climate. The warming waters seem to be affecting the size and distribution of the lobster population. The bottom line is that the lobster population has been declining, which has impacted the local economy and the livelihood of many fishermen.

Last year's state (Maine's) catch fell back almost 14% to 53.9 Million pounds. The Washington Times, August 24, 2004

"...about 60 lobster researchers brainstormed in Groton, Conn. They agreed that...warming water seems to account for the lobster's decline."

"...Last year's state (Maine's) catch fell back almost 14% to 53.9 Million pounds."
**Is the Ferrari Enzo the World’s Fastest?**

<table>
<thead>
<tr>
<th>Engine Type</th>
<th>Top Speed</th>
<th>Fuel Economy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferrari Enzo</td>
<td>217 mph (estimated)</td>
<td>8-12 MPG</td>
</tr>
<tr>
<td>12 Cylinder Gasoline Engine</td>
<td>222.139 mph (measured)</td>
<td>21.2 MPG</td>
</tr>
<tr>
<td>Banks Sidewinder</td>
<td></td>
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<tr>
<td>6 Cylinder Diesel Engine</td>
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</table>
Petroleum Market Forecast
Prices for Oil Head Back to Record Levels

Saudi Call for More Output Does Not Impress Markets

By JONATHAN WEISMAN
Washington Post Staff Writer

Oil prices climbed back into record territory yesterday after energy traders shrugged off pledges by Saudi Arabia to increase production and focused instead on OPEC discord and the shutdown of a major oil platform in the Gulf of Mexico.

Gasoline prices, meanwhile, continued their steady upward march. Pump prices for regular unleaded gasoline increased 4.7 cents in the past week, to a national average price of $2.064 a gallon, the Energy Department's Energy Information Administration said yesterday.

Regular unleaded prices rose nearly a penny in Maryland to an average of $2.015, while Virginia prices climbed 1 cent to $1.934, according to the AAA motor club survey. Experts said it’s likely gasoline prices will keep rising as the United States heads into the vacation-heavy summer driving season, re-

“Experts said it’s likely gasoline prices will keep rising…”
One expert has picked an Armageddon date for the peak of oil production: Thanksgiving 2005. The slow decline in world supplies will start then.

As you might expect, a Campbellian critic can call this "peak oil" visionary. They expect new finds or technology to keep the black stuff flowing. And maybe they’re right. But what of they’re wrong? A permanent shortfall in supplies will severely damage today’s oil-based economy that it makes no sense to wait and see. We need emergency measures. If the Reagan-Gingrich trickle-down experiment does not work, we will be ahead of the game, with more diverse and cheaper sources of energy for future growth.

What might we turn to? The easiest would be efficient diesel cars. Delays less than six years to make up that cut in cost, says Jim Klenk of the American Council for an Energy-Efficient Economy. Renewable also get a 2.50 rate per gallon under this plan.

Wind technology has already shown its worth. If long-armed windmills were driving electric utilities, they would be more air than transportation engines, too.

What’s more, we have an enormous untapped resource—namely, grass. Vice President Dick Cheney famously boasted it in 2000 as more than a "passenger vote"—warm theory not essentiallyy attacked. As wind technology, conservation in the form of more efficient energy use is the fastest growing and most "source" of energy in the United States. When California’s energy crisis struck in 2001, the state on its own cut 15 percent, adjusted for inflation (which would have been cut far more if not for its natural gas prices), thereby cutting their electricity prices by more than double.

Biodiesel has spectacularly shifted oil suppliers, says the ACEEE. He tried to reduce the hours of consumption that were not enough. He proposed the 2006 budget would climb. Its aim was to improve efficiency (Congress restored some of the cut). The 2006 budget is a change again. Required new appliance standards have been cut.

Tying our fuel to one is dangerous ground. Dependence on much more of the things that contribute to the explosion of the Middle East at a cost, some of 1.69 billion. I wish that fuel only export was heard and not. WEF be engaged in that part of the world and oil大海 is being kept.
Diverse Gaseous and Liquid State Fuels

- **Petroleum**
  - gasoline
  - diesel
- **Hydrogen**
  - Tolerant of impurities
- **Hydrogen-enriched**
- **Bio-fuels**

- **Gas-to-liquids**
- **Oil sands**
- **Natural gas**
- **Coal-derived**
- **Shale-derived**
As hydrogen becomes available

Diesel or SI gasoline engines could be modified to operate on hydrogen

- Help enhance commercial aspects of the hydrogen infrastructure
Improved fuel injection equipment
- Most of emission reduction in-cylinder
- Rate shaping of injection charge
- Advanced microcomputer controls
  - Integrated with aftertreatment

Reduced weight
- Moving parts
  - Aluminum block (vehicle mpg)

Variable-nozzle sequential turbochargers

Waste heat utilization
- Turbocompounding
  - High efficiency thermoelectrics

More electric trucks (belt-less engine)

Advanced motor/alternator starter damper (ISAD)
Diesel Engine Waste Heat Energy
Typical Fuel Energy Path in Diesel-Fueled Personal Vehicle

100% Diesel

Combustion

38% Engine

5% Friction & Radiated

24% Coolant

33% Exhaust Gas

Vehicle Operation

33% Mobility & Accessories
- Diesel engine waste heat recovery
  - Turbocompound
    - Mechanical
    - Electrical
  - High-efficiency thermoelectrics - $\Delta T$’s
    - Radiator
    - Lube oil sump
    - Exhaust gas
    - EGR loop
    - Turbocharger discharge
    - Braking
  - Belt-less or more electric engine
  - Integrated starter, alternator/motor, damper (ISAD)
- Major contribution …… 60% efficient diesel
ETC system has been designed and analyzed

- 5% - 10% fuel economy improvement potential
- Opportunity for reduced emissions and improved driveability
Diesel Engine Waste Heat Recovery Utilizing Electric Turbocompound Technology

- More Electric Initiative (MEI)
  - Electrify accessories
  - Reduce fuel consumption

- Electric Turbocharger
  - Enables 5 to 10% Reduction in Fuel Consumption
  - Integrated into MEI Truck

- Modular HVAC
- Shore Power or Inverter
- Down Converter
- Electric Oil Pump
- Compressed Air Module
- Electric Water Pump
- APU
- Starter Generator Motor
Heat-to-electricity conversion efficiency depends on a figure of merit, \( Z \), that is material-specific:

\[
Z = \frac{S^2 \sigma}{k}
\]

- \( S \) = Seebeck Coeff = \( \frac{dV}{dT} \)
- \( \sigma \) = Electrical Conductivity
- \( k \) = Thermal Conductivity

\[
\eta = \left( \frac{T_{hot} - T_{cold}}{T_{hot}} \right) \sqrt{1 + ZT_{avg}} \frac{-1}{\sqrt{1 + ZT_{avg} + \frac{T_{cold}}{T_{hot}}}}
\]

Carnot efficiency.
Recent Breakthrough in Efficiency of TE Materials

Efficiency of Thermoelectric Material (ZT)


Potential with Thin-Film Technologies

Industry Progress – Bulk Semiconductor Technology

Thin-Film Superlattice Technology

Recent Breakthrough in Efficiency of TE Materials

Potential with Thin-Film Technologies

Industry Progress – Bulk Semiconductor Technology

Thin-Film Superlattice Technology

Efficiency of Thermoelectric Material (ZT)

Prediction of Quantum Confinement Effects in Low-D Systems

Note: Conduction is assumed to be along the extended dimension.

For a given $\Delta T$, higher the ZT, higher the heat-to-electric conversion efficiency.

If ZT of 10 can be achieved, a theoretical conversion efficiency of ~35% is possible for $\Delta T$ of ~500°C.
North American personal vehicle market factors

- Emission standard compliance challenge
  - Low sulfur fuel
  - Integrated in-cylinder and aftertreatment
- Fuels availability and costs

Cost of owning and operating
- CO₂ legislation could accelerate diesel sales

Current diesel efficiency ~ 38%

Potential diesel efficiency (by 2014) ~ 60%
- Waste heat utilization major contribution

Comparison of high efficiency, clean diesels with other technologies should be on a comparable time-frame basis
Technology Tree Enabling a 60% Efficient Diesel Engine

- Turbochargers
- Computer controlled fuel injection
- Common Rail Fuel Injection
- Advanced microcomputer controls
- Integrated Starter-Alternator/motor-damper (ISAD)
- Variable-nozzle sequential turbochargers
- More electric trucks (beltless engine)
- Lightweight materials
- HCCI and T-Combustion Regimes
- Rate shaping of injection charge
- Turbocompounding
- High efficiency thermoelectrics

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable
The Diesels are coming, the Diesels are coming!
### Chronology of Diesel Engine Development

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1893</td>
<td>Rudolph Diesel's paper (“the theory and construction of a rational heat engines”), Diesel awarded the patent and built the first compression-ignition engine</td>
</tr>
<tr>
<td>1905</td>
<td>Alfred Buchi patent for practical turbocharger</td>
</tr>
<tr>
<td>1915</td>
<td>Buchi’s prototype: first turbocharged diesel engine</td>
</tr>
<tr>
<td>1927</td>
<td>Robert Bosch developed the first fuel injection system, allowing metering of fuel</td>
</tr>
<tr>
<td>1927</td>
<td>First turbocharged diesel heavy-duty truck engine</td>
</tr>
<tr>
<td>1957</td>
<td>First production high-pressure diesel FIE</td>
</tr>
<tr>
<td>1980’s-Present</td>
<td>Rate shaping with FIE, including pilot injection (reduced noise and NO&lt;sub&gt;x&lt;/sub&gt;)</td>
</tr>
<tr>
<td></td>
<td>Emission reduction aftertreatment</td>
</tr>
<tr>
<td>1983</td>
<td>First electronic diesel control (EDC)</td>
</tr>
<tr>
<td>1990’s</td>
<td>Computer controlled FIE pioneered by DDC</td>
</tr>
<tr>
<td>Late-1990’s to Mid-2000’s</td>
<td>HCCI and low-temperature regime combustion advances</td>
</tr>
<tr>
<td></td>
<td>Waste heat utilization: Turbocompounding and bulk semiconductor thermoelectrics</td>
</tr>
<tr>
<td></td>
<td>Beltless engines or more electric trucks</td>
</tr>
<tr>
<td></td>
<td>Integrated starter, alternator/motor, damper (ISAD) development</td>
</tr>
<tr>
<td>1999</td>
<td>Common rail FIE for passenger cars</td>
</tr>
<tr>
<td>2004</td>
<td>DOE contract for high efficiency thermoelectric waste heat recovery</td>
</tr>
<tr>
<td>2005</td>
<td>BMW introduces electric water pump (Series 5)</td>
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