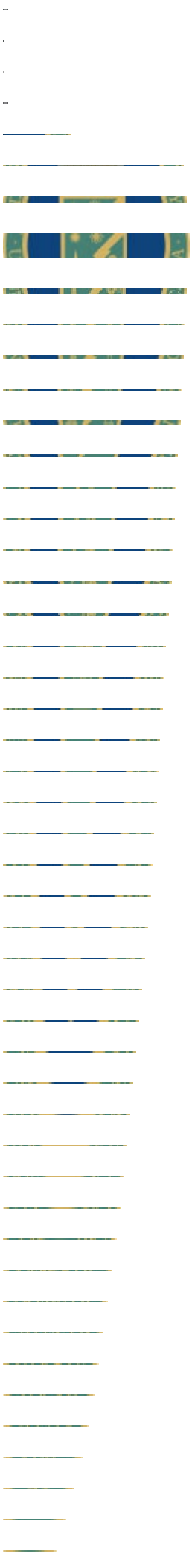
Fuels of the Future for Cars and Trucks

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





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What Energy Source Will Power Engines of the Future?

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

q No other fuels:

Ø Are so abundant

Ø Have such a high energy density

Ø Have such a high power density

Ø Store energy so efficiently and conveniently Ø Release their stored energy so readily (rapid oxidation/combustion)

Ø Have existing infrastructure

Ø Are so easily transported

2

Potential Energy Carriers

q Currently, we see only 2 potential non-carbon based energy carriers that have the requisite volume needed to replace petroleum fuels Ø

Hydrogen

Ø

Electricity

3

Energy Density of Fuels

1,200

1058

990

1,000

950

922

3

800

683

635

594

600

488

Thousand Btu per ft

400

270

266

200

68

16

0

F-T

Diesel

Biodiesel

Biorenewable

LPG

Ethanol

CNG (@ 3626 psi)

Diesel Fuel

Compressed NiMH

Diesel

Gasoline Propane

LNG

Ethanol Methanol Liquid H

CNG

2

Diesel

(@ 3626 psi) Hydrogen

4

Battery

(@ 3626 psi)

Energy Density of Fuels

Normalized to Diesel Fuel

1.20

100.0%

1.00

93.6% 89.8% 87.2%

0.80

64.6% 60.0%

0.60

56.2%

46.1%

0.40

Percent of Diesel Fuel Energy Density 25.5% 25.1%

0.20

6.4%

1.3%

0.00

F-T Biorenewable

Diesel

Diesel Fuel

Biodiesel

Gasoline

LPG

Propane

LNG

Ethanol

Ethanol

CNG (@ 3626 psi)

Methanol

CNG

Compressed NiMH

Diesel

Liquid H2

Diesel

(@ 3626 psi) Hydrogen

5

Battery

(@ 3626 psi)

Comparison of Energy Conversion Efficiencies Fuel Cell-Stored Hydrogen

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

Today's Capability

Injection

Conventional ICE

Projected Capability

Conventional Spark

(2004)

Ignition ICE

0%

10%

20%

30%

40%

50%

60%

70%

Peak Thermal Efficiency (%)

6

* 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 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)

0

20

40

60

80

100

Today's Capability

Comparison of Miles Driven

(Same Volume of On-Board Fuel)

Projected Capability

7

(2004)

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 8







Minivan



Utility van



Crew compartment pick-up



Full-size pick-up



Mini-bus



Step Van



Large Walk-in



City Delivery



Bucket



Rack



Single Axle Van



Beverage



School Bus



Stake Body



Walk-in



City Delivery



Mini-bus



Home Fuel



Refuse



City Transit Bus



Medium Conventional



Conventional Van



Large Walk-in



City Delivery



Landscaping/Utility



Dump



Cement



Heavy Conventional



COE Sleeper

Truck Classification (by Gross Vehicle Weight) CLASS 1

CLASS 5

6,000 lbs. & Less

16,001-19,500 lbs.

CLASS 2

CLASS 6

6,001-10,000 lbs.

19,501-26,000 lbs.

CLASS 3

CLASS 7

10,001-14,000 lbs.

26,001-33,000 lbs.

CLASS 4

CLASS 8

14,001-16,000 lbs.

33,001 lbs. & Over

Cars and Light-Duty Trucks vs. Heavy-Duty Trucks Payload to

Common GVW

Unloaded

Vehicle Type

Payload (lbs)

Unloaded Weight

(lbs)

Weight (lbs)

Ratio (%)

Family Sedan – 5

3,400

~ 3,100

~ 1,000

32

passengers

(5 x 200 lb)

Light Truck

5,150

4,039

1,111

28

Class 2b Truck

8,600

4,962

3,638

73

Class 3 Truck

11,400

5,845

5,600

96

Class 4 Truck

15,000

6,395

8,605

135

3-axle single unit

50,000 to 65,000

~ 22,600

27,400 to 42,400

121 to 188

truck

4-axle single unit

62,000 to 70,000

~26,400

35,600 to 43.600

135 to 165

truck

5-axle tractor semi- 80,000 to 99,000

~ 30,500

49,500 to 68,500

162 to 225

trailer

10

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) 11

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 ft3

Front Axle Capacity is 12,000 lb, Rear Axle Capacity is 38,000 lb LMP Batteries

Performance

Battery Space

Battery Weight

(ft3)

(% of cargo)

(lb)

(% of total capacity)

Range - *500 miles*

358

5.9%

42,635

85%

Assumptions: Truck: 310 HP, 6 mpg fuel economy, 45% average engine thermal efficiency, Batteries: Spec. Power 241

W/kg, Energy Density: 143 Wh/l, Spec. Energy 121 Wh/kg 12

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

NaBH + 2H O 4H + NaBO

4

2

2

2

catalyst

q Sodium borohydride (a salt) is dissolved in water where it stays until gaseous hydrogen is needed

q When H is needed, the solution is pumped over a catalyst 2

q The H2 gas comes out and leaves behind sodium borate (another salt) which remains dissolved in water and goes to the spent fuel tank.

q NaBH

2H O

4

2

Na 23

2O 32

We have to carry 73.8kg

B 10.8

2H

4

for every 8kg of Hydrogen

2

4H

4

which is about 11% by weight

37.8

36

or <50% that of methane, CH4

13

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

NaBH + 2H O 4H + NaBO

4

2

2

2

catalyst

Claims

q Sodium borohydride is derived from borax, which is abundant and widely available

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

q Sodium borate can be recycled into new sodium borohydride **The Rest of the Story**

q To recycle sodium borate into new sodium borohydride requires reduction reaction in a kiln at 900oC under highly corrosive environment

q Coke or methane (CH4) is needed

CH + NaBO

900C

NaBH + CO

4

2

4

2

q It takes more energy to make sodium borohydride than the 14

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!

13

Fuel Cell/H from NaBH in Water –

2

4

Twenty-six 84 gallon tanks (13 tanks containing NaBH /water solution weighing 15,058 lbs.; 13 tanks for spent fuel).

4

15

Batteries not included (but required for fuel cell-hybrid configuration).

To Enable Replacement of Petroleum as Primary Energy Carrier for Ground Transportation Fuel Cells for Heavy Vehicle Propulsion: Practical Considerations

q Hydrocarbon fuels need to be reformed on board the vehicle to produce H2

q Furthermore, water gas shift is necessary to convert the energy content in the carbon-carbon bonds to H2

q Powertrain hybridization may be required for heavy vehicle acceleration

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Energy Embodied in Carbon-Carbon Bonds Increases with Hydrocarbon Molecular Weight C H

+ (n/2)O

nCO + (n+1)H -) *H*

n

2n+2

2

2

70

65

60

55

50

45

40

35

30

Percent of Energy in Reaction Products 25

Ethane

Methane

Propane

Butane

Pentane

Hexane

Heptane

Octane

Nonane

Decane

Carbon Monoxide

Hydrogen

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On-Board Reforming of Hydrocarbons to Produce Hydrogen for the Fuel Cell Partial oxidation of a hydrocarbon into CO and H2

C H

+ (n/2)O

nCO + (n+1)H -) *H*

n

2n+2

2

2

POx

Water-gas shift reaction of CO to produce more H2

(also produces CO)

2

CO + H O +) *H*

H + CO

2

2

2

Steam

18

To Enable Replacement of Petroleum as Primary Energy Carrier for Ground Transportation Research Breakthroughs Are Needed q Major technological breakthroughs are needed if hydrogen fuel cells are to displace the diesel engine Ø Electrolytic/water "splitting" hydrogen production (renewable, nuclear)

Ø Low pressure on-board gaseous fuel storage OR

on board highly efficient hydrocarbon fuel reformer Ø Greatly reduced catalyst loading in fuel stack/reformer (cost reduction)

q Major technological breakthroughs are needed if electrical energy is to displace the diesel engine Ø Electrical generation from non-fossil resources (renewable, nuclear)

Ø On board high energy/high power density electric storage

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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* 20

Energy Efficiency Forum, National Press Club, June 12, 2002

Heavy-Duty Diesel – Increasingly Dominant Engine for Heavy Vehicles q Improved fuel quality

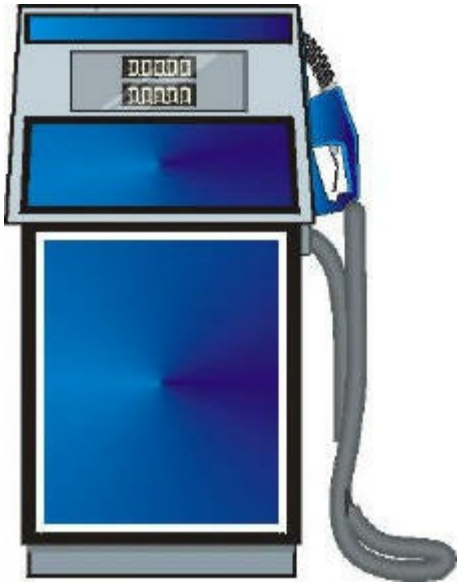
q Combustion technology

Ø DI rate shaping/electronic controls Ø HCCI (part load)

q Aftertreatment technology

q Hybridization

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Future Liquid Fuels Strategy?

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

Efficient Low

Emission Heavy

Multiple

Advanced High-

Clean Diesel

Vehicles

Alternative

Efficiency Clean Diesel

Fuels/Blends

Feedstocks

Engine Technologies

Heavy Truck

Synthesis gas

route to:

Exhaust Treatment

• Coal

• Biomass

Liquid Fuels

• Natural Gas

l **Common**

Diesel Fuel

Specification

Fuel Quality

l

Diesel Engine

Uses

• Petroleum

Existing

Construction/

Conventional

In-cylinder Processes

Infrastructure

Farming Vehicles

petroleum

refining

Locomotive

Fischer-Tropsch Fuel Production

New Fischer-Tropsch production with partial oxidation and Cobalt-based catalysts reduces CO formation 2

New Syngas Production

H /CO ratio

2

catalytic partial oxidation CH + 1/2 O

CO + 2H + heat

4

2

2

near-ideal

H /CO ratio

steam reforming CH + H O Co-based 2H

+ CO

2

4

2

2

non-ideal

Fischer-Tropsch Reaction

CO + H

Co catalyst (H C-) + H O

+ heat

2

2

n

2

(g)

23

Fuels for the Next 10 Years

q Low sulfur diesel fuel (15 ppm)

Dominant

q Low sulfur gasoline (30 ppm)

q Niche fuels in heavy-duty market

Ø Natural Gas (as gas - CNG) – local delivery fleet vehicles

Ø LNG (long haul fleet vehicles)

Ø Biodiesel (B20) (long haul vehicles, marine applications)

q Natural gas derived liquids

Ø Fischer Tropsch (blendstock for petroleum Diesel fuel)

q Ethanol as replacement oxygenate for MTBE in gasoline

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Summary

What Will Be the Fuels of the Future?

q In the Near Term

Ø Low sulfur gasoline and low sulfur diesel q In the Mid to Long Term

Ø Hydrogen from safe on-board storage appears promising for light-duty vehicles (FreedomCAR) Ø Breakthroughs are necessary in the economical production and intermediate storage (e.g., CH OH, 3

NaBH) of hydrogen for light-duty vehicles 4

q For the Foreseeable Future (Next 10 - 25 years)?

Ø With no alternative yet identified, it appears that hydrocarbon-based fuels (from a variety of feedstocks) will be the future fuels for heavy-duty 25

vehicles