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

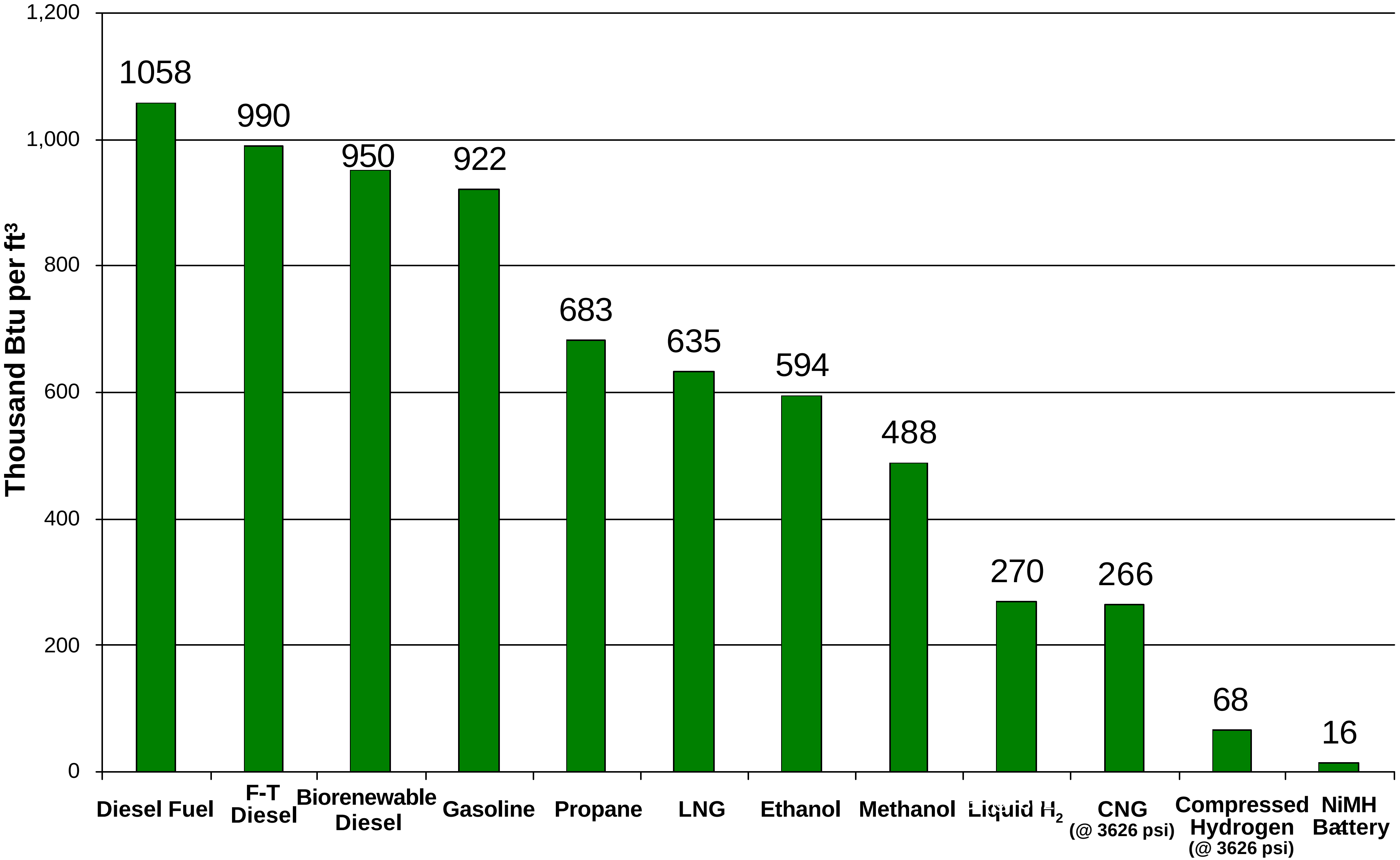
What Energy Source Will Power Engines of the Future?

- 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

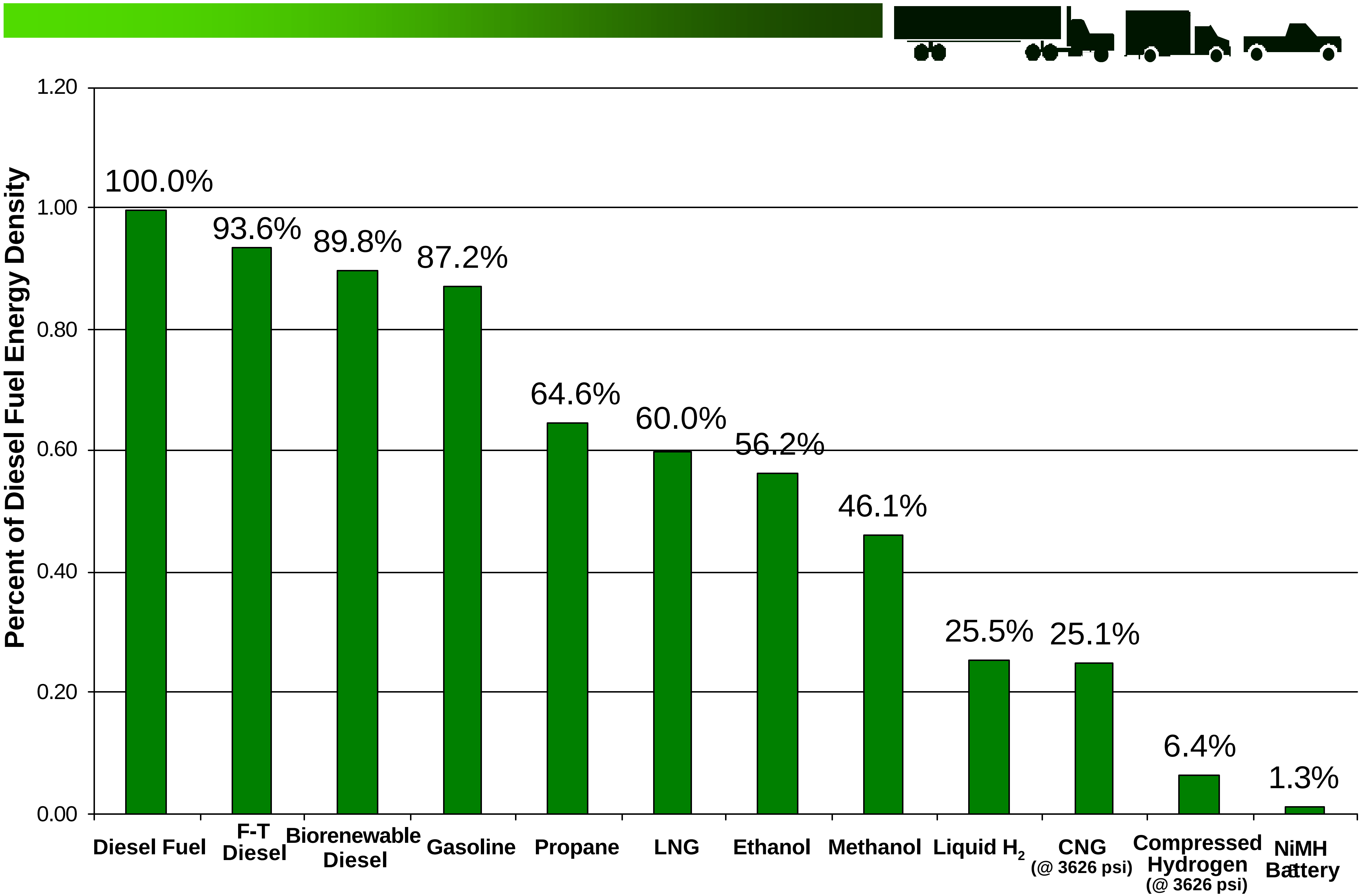
Potential Energy Carriers

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

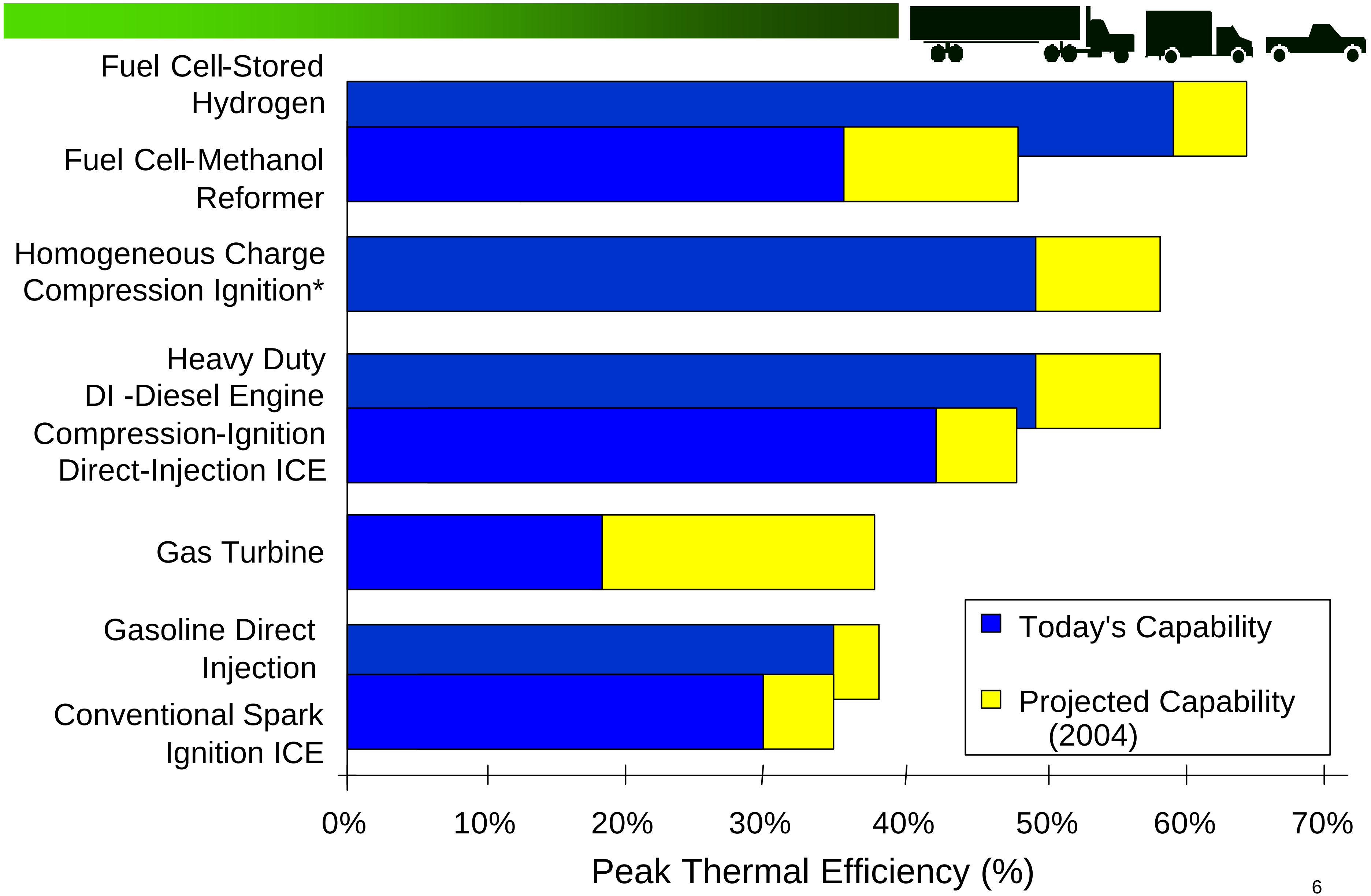
Energy Density of Fuels



Energy Density of Fuels
Normalized to Diesel Fuel

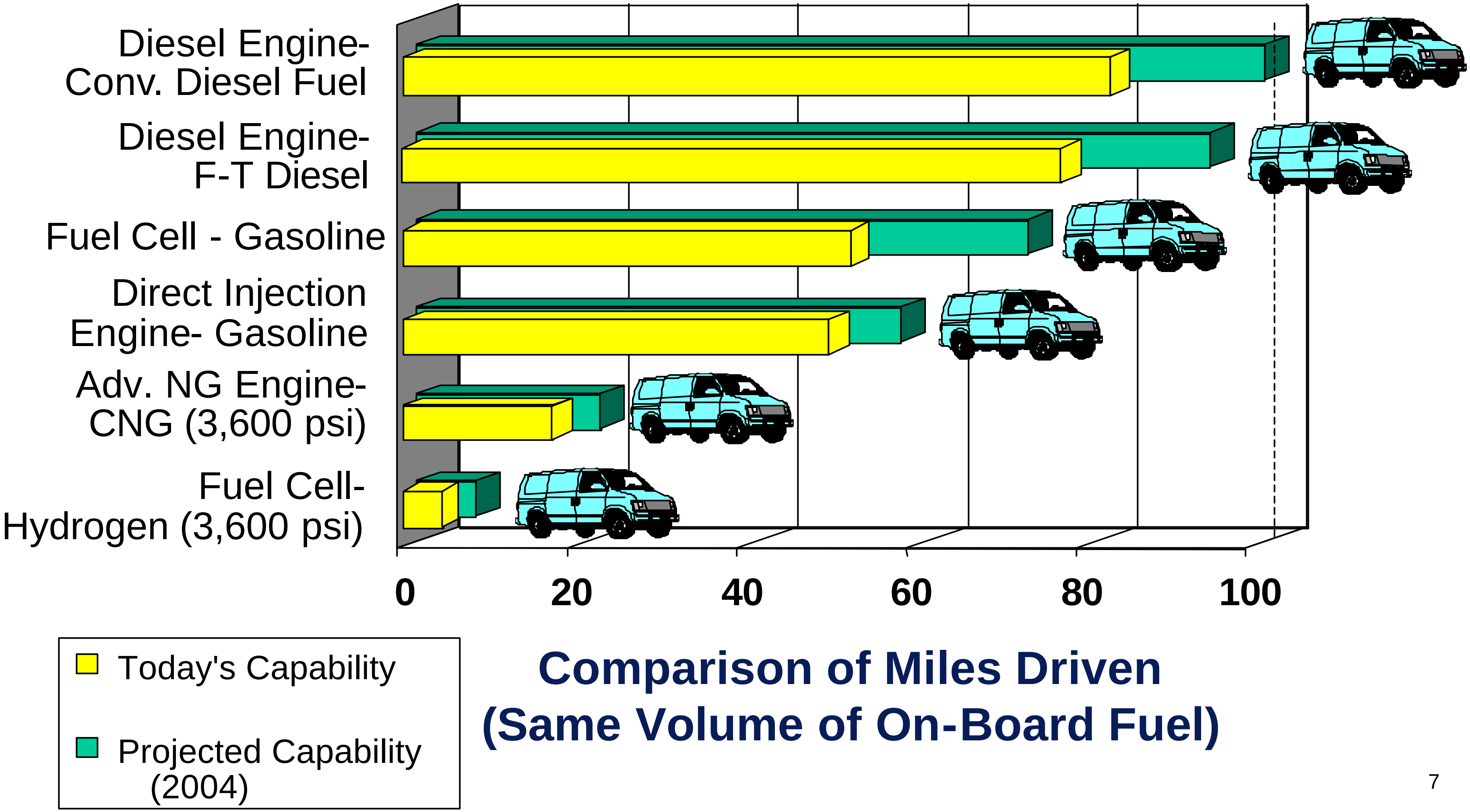


Comparison of Energy Conversion Efficiencies



* 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)

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

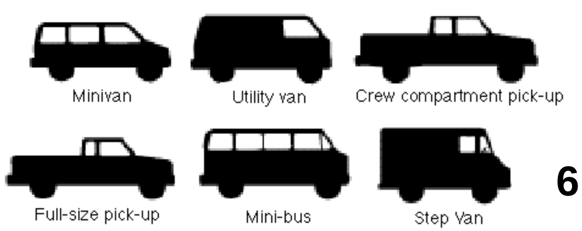
Truck Classification (by Gross Vehicle Weight)

CLASS 1

6,000 lbs. & Less

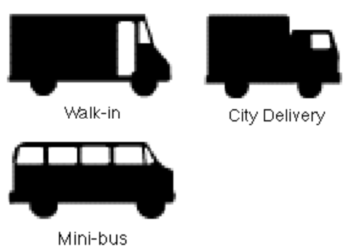
CLASS 2

6,001-10,000 lbs.



CLASS 3

10,001-14,000 lbs.



CLASS 4

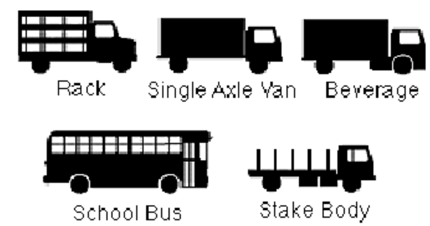
14,001-16,000 lbs.

CLASS 5

16,001-19,500 lbs.

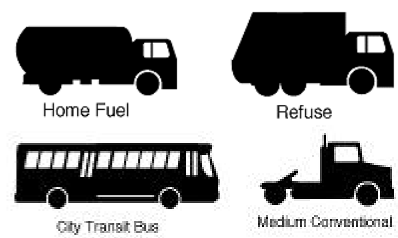
CLASS 6

19,501-26,000 lbs.



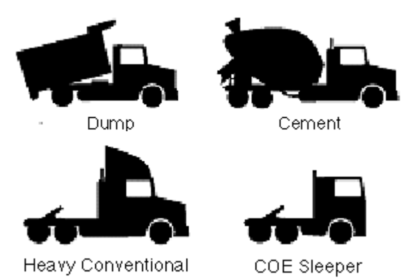
CLASS 7

26,001-33,000 lbs.



CLASS 8

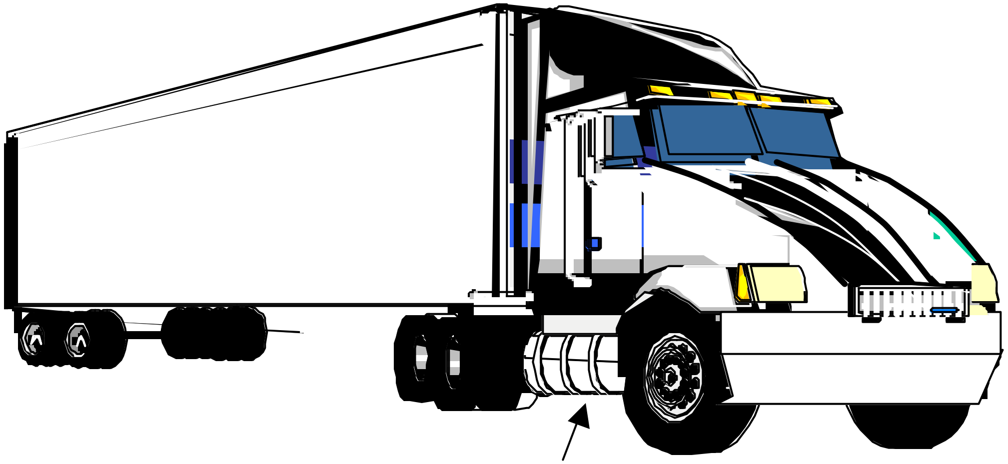
33,001 lbs. & Over



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

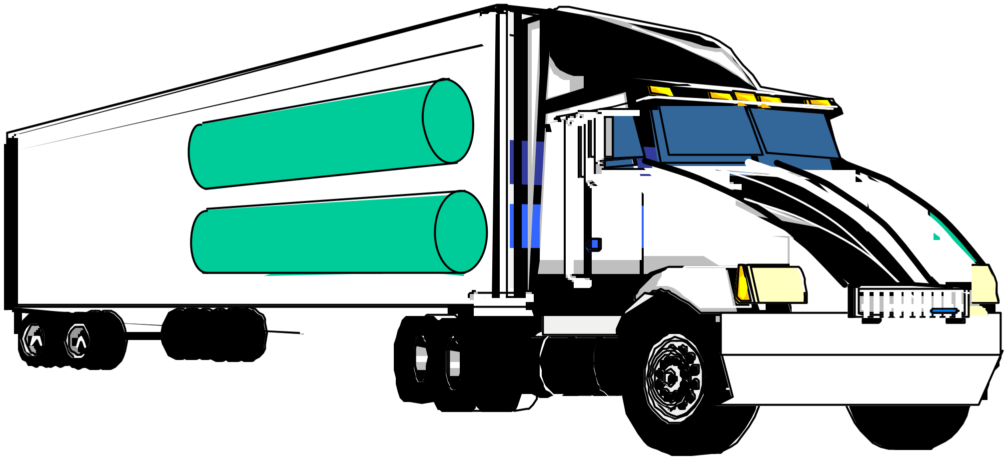
Vehicle Type	Common GVW (lbs)	Unloaded Weight (lbs)	Payload (lbs)	Payload to Unloaded Weight Ratio (%)
Family Sedan – 5 passengers	3,400	~ 3,100	~ 1,000 (5 x 200 lb)	32
Light Truck	5,150	4,039	1,111	28
Class 2b Truck	8,600	4,962	3,638	73
Class 3 Truck	11,400	5,845	5,600	96
Class 4 Truck	15,000	6,395	8,605	135
3-axle single unit truck	50,000 to 65,000	~ 22,600	27,400 to 42,400	121 to 188
4-axle single unit truck	62,000 to 70,000	~26,400	35,600 to 43.600	135 to 165
5-axle tractor semi-trailer	80,000 to 99,000	~ 30,500	49,500 to 68,500	162 to 225

Volume of Fuel Needed for Equivalent Range
(1,000 mile range)



Diesel Fueled – Two (one on each side) 84 gallon tanks (23 ft^3)

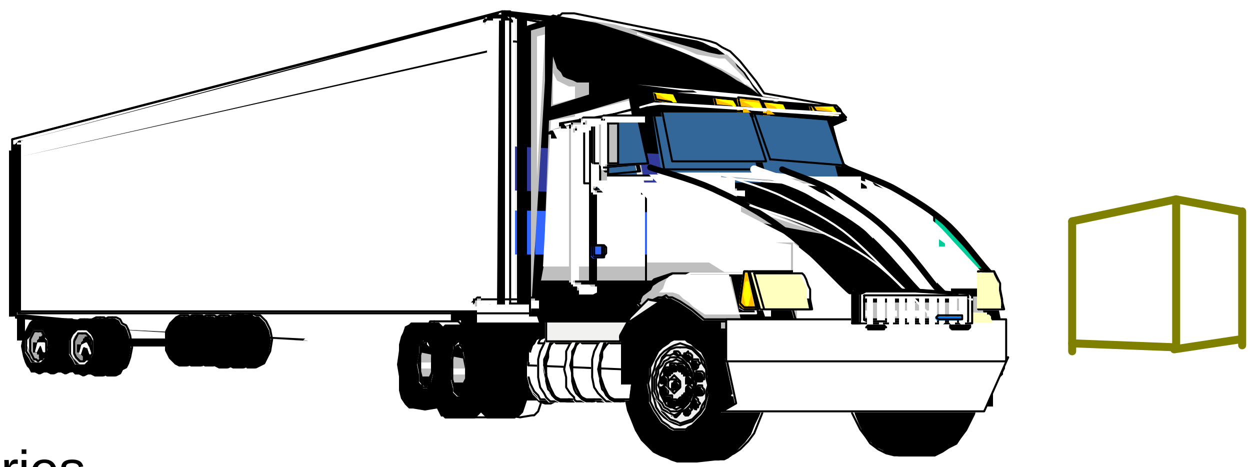
Loss of revenue cargo space!



Fuel Cell/Hydrogen Fueled – Two 1,180 gallon tanks (316 ft^3) 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



LMP Batteries

Performance	Battery Space		Battery Weight	
	(ft^3)	(% 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

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

$$NaBH_4 + 2H_2O \xrightarrow[\text{catalyst}]{} 4H_2 + NaBO_2$$

- Sodium borohydride (a salt) is dissolved in water where it stays until gaseous hydrogen is needed
- When H_2 is needed, the solution is pumped over a catalyst
- The H_2 gas comes out and leaves behind sodium borate (another salt) which remains dissolved in water and goes to the spent fuel tank.
- $NaBH_4$ $2H_2O$

Na	23	2O	32
B	10.8	$2H_2$	4
4H	4		
	37.8		36

We have to carry 73.8kg for every 8kg of Hydrogen which is about 11% by weight or <50% that of methane, CH_4

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

$$NaBH_4 + 2H_2O \xrightarrow[\text{catalyst}]{} 4H_2 + NaBO_2$$

Claims

- 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

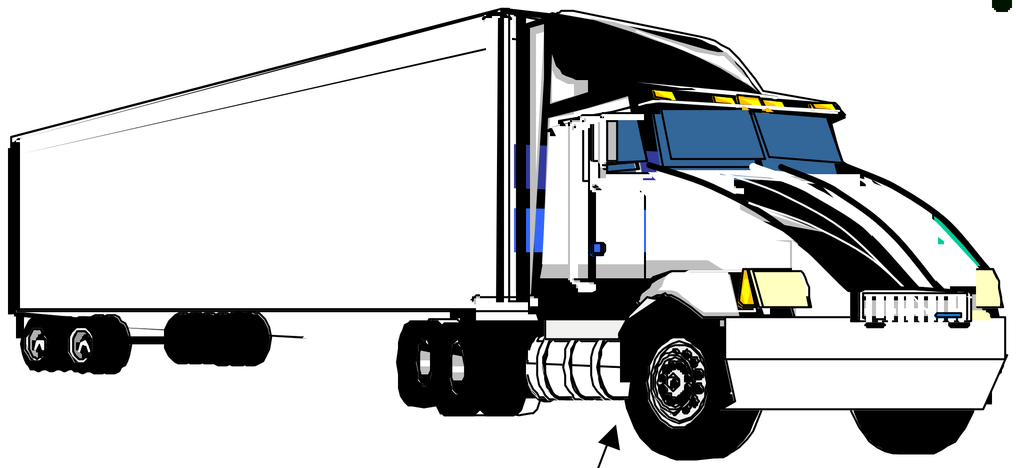
The Rest of the Story

- To recycle sodium borate into new sodium borohydride requires reduction reaction in a kiln at 900ºC under highly corrosive environment
- Coke or methane (CH_4) is needed

$$CH_4 + NaBO_2 \xrightarrow{900C} NaBH_4 + CO_2$$

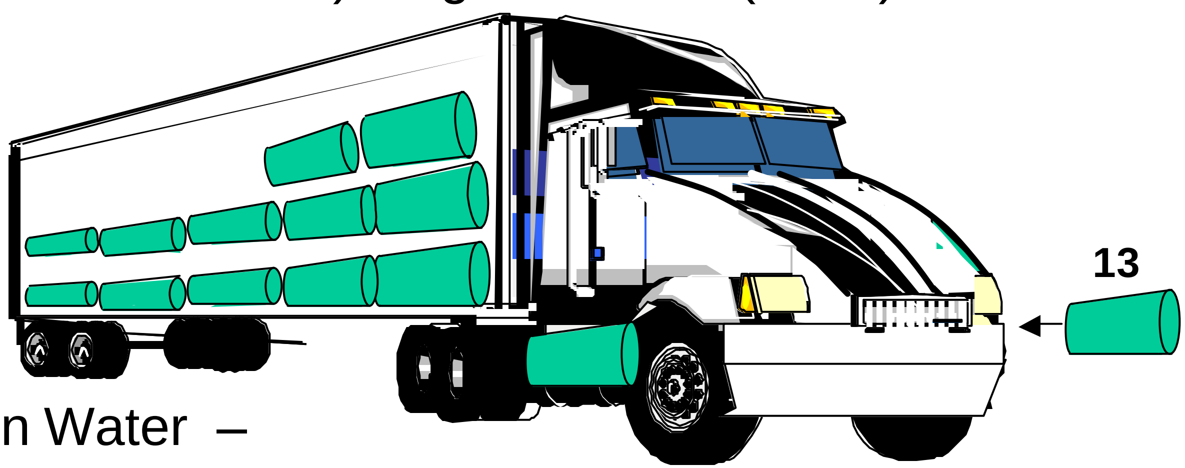
- It takes more energy to make sodium borohydride than the energy released (or recovered) in the fuel cell

Volume of Fuel Needed for Equivalent Range
(1,000 mile range)



Diesel Fueled – Two (one on each side) 84 gallon tanks (23 ft^3)

Loss of revenue cargo space!



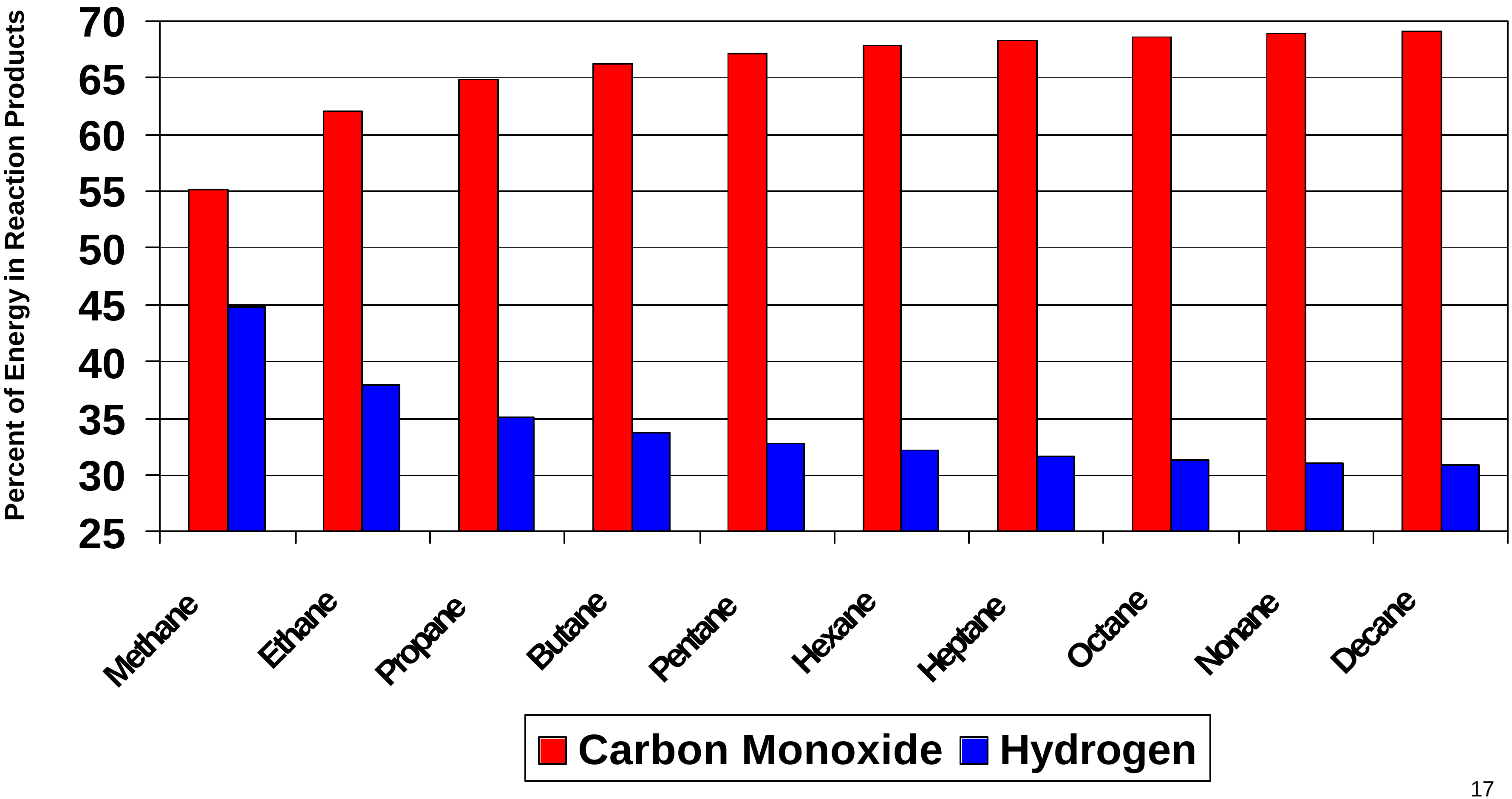
Fuel Cell/H_2 from $NaBH_4$ in Water –
Twenty-six 84 gallon tanks (13 tanks containing $NaBH_4$/water solution weighing 15,058 lbs.; 13 tanks for spent fuel).
Batteries not included (but required for fuel cell-hybrid configuration).

Fuel Cells for Heavy Vehicle Propulsion: Practical Considerations

- Hydrocarbon fuels need to be reformed on board the vehicle to produce H_2
- Furthermore, water gas shift is necessary to convert the energy content in the carbon-carbon bonds to H_2
- Powertrain hybridization may be required for heavy vehicle acceleration

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

$$C_nH_{2n+2} + (n/2)O_2 \longrightarrow nCO + (n+1)H_2 - \;)\, H$$



On-Board Reforming of Hydrocarbons to Produce Hydrogen for the Fuel Cell

Partial oxidation of a hydrocarbon into CO and H_2

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

Water-gas shift reaction of CO to produce more H_2 (also produces CO_2)

$$CO + \underset{Steam}{H_2O} + \,)\,H \longrightarrow H_2 + CO_2$$

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."

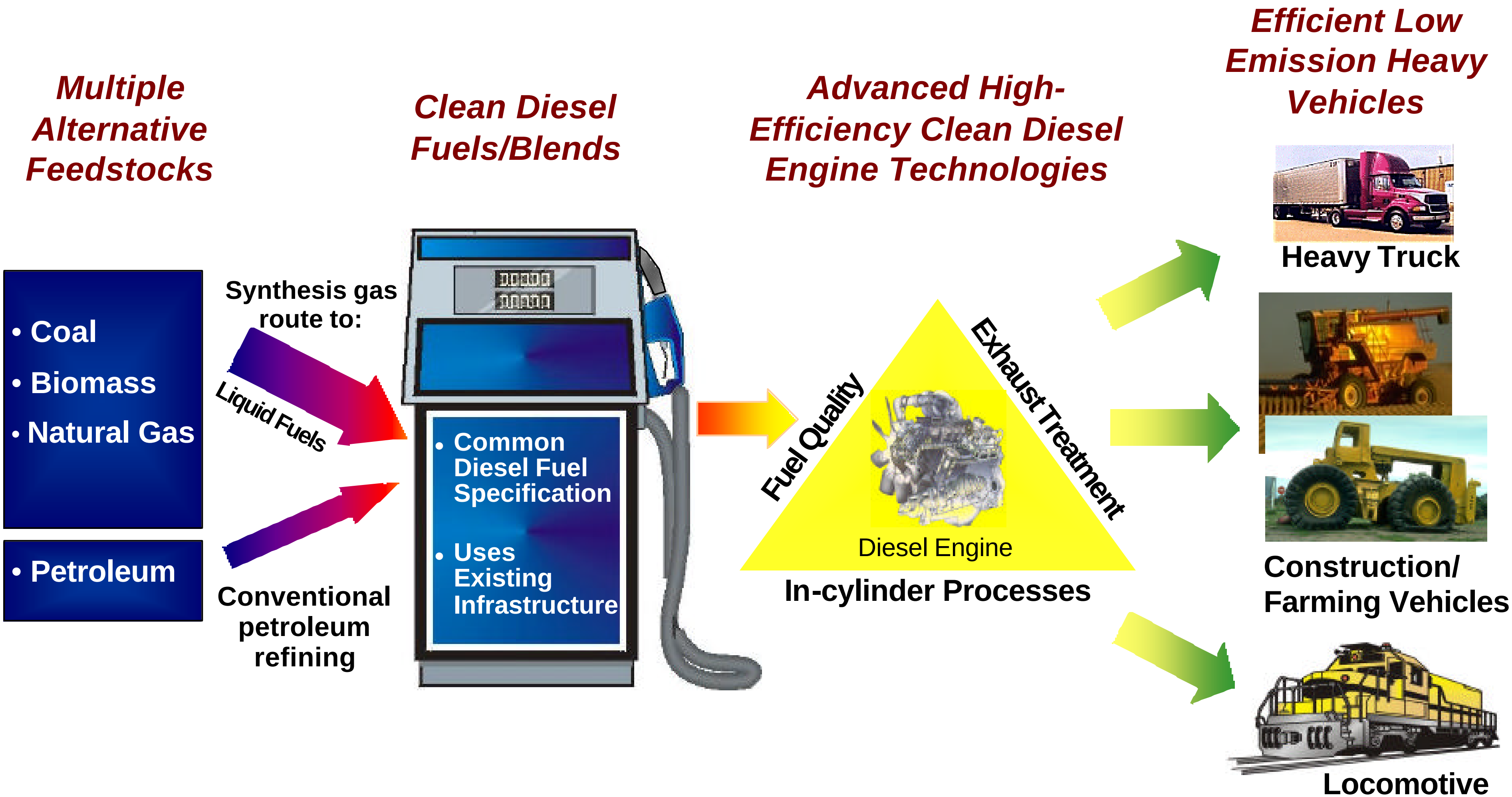
\- *Remarks of Energy Secretary Spencer Abraham at the 13th Annual Energy Efficiency Forum, National Press Club, June 12, 2002*

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



Fischer-Tropsch Fuel Production

New Fischer-Tropsch production with partial oxidation and Cobalt-based catalysts reduces CO_2 formation

New Syngas Production

catalytic partial oxidation $CH_4 + 1/2\ O_2 \rightarrow CO + 2H_2$ + heat — H_2/CO ratio near-ideal

steam reforming $CH_4 + H_2O \underset{}{\xrightleftharpoons{\text{Co-based}}} 2H_2 + CO$ — H_2/CO ratio non-ideal

Fischer-Tropsch Reaction

$CO + H_2 \xrightarrow{\text{Co catalyst}} (H_2C\text{-})_n + H_2O_{(g)}$ + heat

Fuels for the Next 10 Years

- Low sulfur diesel fuel (15 ppm)
- Low sulfur gasoline (30 ppm)

Dominant

- 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

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_3OH, $NaBH_4$) 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