Fuel Efficiency In Transportation Systems

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Outline of Lecture

- The Issue – Global Warming, Motivation for Transportation Efficiency
- Carbon Emissions by Light Duty Vehicles
- Alternate Engine Concepts
- Alternate Fuels
- Alternate Power Sources
- Role of Aerodynamic Efficiency
The Issue
**Milankovitch cycles**

*Caused by gravitational attraction between planets of the solar system and Earth due to changes in the eccentricity of the Earth’s orbit, obliquity of the Earth’s axis and precession of the Earth’s axis of rotation.*

- **Wobble Cycles** 19,000 & 23,000 Yrs.
- **Tilt Cycle** 41,000 Yrs.
- **Earth Orbit** 100,000 & 400,000 Yrs.

Below a chart showing CO₂ & temperature of Antarctica ice surface by year.
Greenhouse Gas Emissions

Note: Pre-Industrial Levels 260-280 ppm CO₂ eq.

Fossil Fuel Combustion Sources of CO₂
(% contributions for 2000–2004)
• Solid fuels (e.g. coal): 35%
• Liquid fuels (e.g. gasoline): 36%
• Gaseous fuels (e.g. natural gas): 20%
• Flaring gas industrially and at wells: <1%
• Cement production: 3%
• Non-fuel hydrocarbons: <1%
• Shipping and air transport: 4%

In a typical year, the daily rate of ice loss starts to slow in August as the Arctic begins to cool. By contrast, in August 2008, the daily decline rate remained steadily downward and strong.

Source: National Snow & Ice Data Center

“To stay below the threshold for melting of the ice sheets in Greenland and West Antarctica, we need to reduce CO₂ emissions by 80% and achieve a diet of no more than 30 pounds of CO₂ per person per day.”
Carbon Emissions by Light Duty Vehicles
# US Transportation Energy Book Data

(US Dept. of Energy, June 2008)

<table>
<thead>
<tr>
<th>Transport Mode</th>
<th>Average Passengers Per Vehicle</th>
<th>Efficiency Per Passenger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vanpool</td>
<td>6.1</td>
<td>1322 BTU/mi, 2.7 L/100 km (87 MPGeUS)</td>
</tr>
<tr>
<td>Motorcycles</td>
<td>1.2</td>
<td>1855 BTU/mi, 3.8 L/100 km (62 MPGeUS)</td>
</tr>
<tr>
<td>Rail (Amtrak)</td>
<td>20.5</td>
<td>2650 BTU/mi, 5.4 L/100 km (43 MPGeUS)</td>
</tr>
<tr>
<td>Rail (Transit Light &amp; Heavy)</td>
<td>22.5</td>
<td>2784 BTU/mi, 5.7 L/100 km (41 MPGeUS)</td>
</tr>
<tr>
<td>Rail (Commuter)</td>
<td>31.3</td>
<td>2996 BTU/mi, 6.1 L/100 km (38 MPGeUS)</td>
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<tr>
<td>Air</td>
<td>96.2</td>
<td>3261 BTU/mi, 6.7 L/100 km (35 MPGeUS)</td>
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<tr>
<td>Cars</td>
<td>1.57</td>
<td>3512 BTU/mi, 7.2 L/100 km (33 MPGeUS)</td>
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<tr>
<td>Personal Trucks</td>
<td>1.72</td>
<td>3944 BTU/mi, 8.1 L/100 km (29 MPGeUS)</td>
</tr>
<tr>
<td>Buses (Transit)</td>
<td>8.8</td>
<td>4235 BTU/mi, 8.7 L/100 km (27 MPGeUS)</td>
</tr>
</tbody>
</table>

**Passenger Miles Per Gallon (PMPG)**

- Bicycling - 653 PMPG
- Walking - 235 PMPG
- Cruise Ship - 17 PMPG
- Gulfstream G550 - 16 PMPG
Global Fossil Carbon Emissions by Economic Sector

These estimates include only CO$_2$ emissions from fossil fuel use, and so exclude emissions from biofuel use or deforestation.

- Light duty vehicle emission shares by region are estimates for 2000 from WBCSD (2004).
- Other sectors include commercial, public services, agriculture and energy industries other than electricity and heat production.

Source: DeCicco et. al., Global Warming on the Road
US Crude Oil Imports Per Day
25 Thousand Barrels in FY 2006

Sources of US Oil Imports
Note: US Produces 4 Million per Day

- CANADA - 19%
- MEXICO - 10.3%
- VENEZUELA - 9%
- COLOMBIA - 1.3%
- ECUADOR - 1.3%
- BRAZIL - 1.7%
- NIGERIA - 9%
- LIBYA - 1%
- ALGERIA - 4.7%
- CHAD - 1%
- IRAQ - 5%
- SAUDI ARABIA - 10.5%
- KUWAIT - 1.4%
- NOR. 1%
- U.K. - 1.7%
- NETH. 1.4%
- RUSSIA 3%

58% FROM TOP 5
87% FROM TOP 18

Product Distribution From a Barrel of Oil

what's in a barrel of oil

- jet fuel 4.1 gallons
- distillate fuel oil 9.2 gallons
- gasoline 19.5 gallons
- other 0.3 gal.
- kerosene 0.2 gal.
- lubricants 0.5 gal.
- feedstocks 1.2 gal.
- asphalt/road oil 1.3 gal.
- petroleum coke 1.8 gal.
- still gas 1.9 gal.
- liquefied gases 1.9 gal.
- residual fuel oil 2.3 gal.

Source: AIP. Totals more than 44 gals. because of “processing gain”

Source: Gibson Consulting

Note: 42 gallons of crude oil per barrel
## Consumption of Petro Products (Thousand Barrels Per Day)

<table>
<thead>
<tr>
<th>Region</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America</td>
<td>24207.13</td>
<td>25045.96</td>
<td>25220.97</td>
<td>25070.75</td>
</tr>
<tr>
<td>Central &amp; South America</td>
<td>5195.683</td>
<td>5349.07</td>
<td>5481.752</td>
<td>5691.713</td>
</tr>
<tr>
<td>Eurasia</td>
<td>3910.225</td>
<td>4040.797</td>
<td>4158.806</td>
<td>4197.5</td>
</tr>
<tr>
<td>Middle East</td>
<td>5286.231</td>
<td>5539.414</td>
<td>5808.184</td>
<td>6065.3</td>
</tr>
<tr>
<td>Africa</td>
<td>2715.094</td>
<td>2819.461</td>
<td>2972.248</td>
<td>2984.93</td>
</tr>
<tr>
<td>Asia &amp; Oceania</td>
<td>22158.91</td>
<td>23353.17</td>
<td>23940.05</td>
<td>24526.12</td>
</tr>
<tr>
<td>World</td>
<td>79660.39</td>
<td>82407.67</td>
<td>84004.87</td>
<td>84979.39</td>
</tr>
</tbody>
</table>

Energy Information Administration
Factors Determining Auto Sector CO$_2$ Emissions

- Travel Demand ($2.6 \times 10^{12} \text{ miles/year}$)
- Fuel Use Rate (51 gallons/1000 miles)
- Fuel Carbon Content (5.3 pounds of carbon/gallon)

Note: FY 2004 US Auto Sector Results Where 314 MMTc Were Emitted

Source: DeCicco et. al., Global Warming on the Road
Amount of CO₂ Emitted Per Gallon

Code of Federal Regulations (40 CFR 600.113):
Gasoline carbon content per gallon: 2,421 grams
Diesel carbon content per gallon: 2,778 grams

To calculate CO₂ emissions from a gallon of fuel, carbon emissions are multiplied by the ratio of the molecular weight of CO₂ (m.w. 44) to the molecular weight of carbon (m.w.): 44/12.

CO₂ emissions from a gallon of gasoline = 2,421 grams X 0.99 X (44/12) = 8,788 grams = 8.8 kg/gallon = 19.4 pounds/gallon.

CO₂ emissions from a gallon of diesel = 2,778 grams X 0.99 X (44/12) = 10084 grams = 10.1 kg/gallon = 22.2 pounds/gallon.
Conventional Automotive Engine Cycles

4-Stroke Engine Concept

The four-stroke engine was first patented by Eugenio Barsanti and Felice Matteucci in 1854. The two-stroke cycle was patented by Dugald Clerk in 1878.

Idealized Thermo Cycle
4-Stroke SI Engine

Otto Cycle Pv Diagram, Nicolaus Otto, 1876

Idealized Thermo Cycle
4-Stroke CI Engine

Diesel Cycle Pv Diagram, Rudolph Diesel, 1892

Obert, Internal Combustion Engines, 1970
Cycle Pad Design Library
**Ideal Otto Cycle**

Stoichiometric Combustion of Gasoline with AIR

\[ C_8H_{18} + 12\frac{1}{2}O_2 + 47N_2 \rightarrow 8CO_2 + 9H_2O + 47N_2 \]

\[ Q_{A\text{rev}} = c_v (T_3 - T_2) \]
\[ Q_{R\text{rev}} = c_v (T_1 - T_4) \]

\[ \eta_t = \frac{Q_A + Q_R}{Q_A} = 1 - \frac{T_1}{T_2} = 1 - \frac{1}{r_v^{\gamma-1}} \]

Note: \( r_v \) is the engine compression ratio

**Example:** \( r = 8, \ Ta = 540^0R, \ Pa = 14.7 \) psia

\[ \eta_t = 1 - \frac{1}{r_v^{\gamma-1}} = 1 - \frac{1}{8^{0.4}} = 0.565 \]

or 56.5%

Factoring in transmission & drive train overall gas power auto efficiency 17%

Obert, Internal Combustion Engines, 1970
Ideal Diesel Cycle

\[ Q_{Arev} = c_v (T_3 - T_2) \]
\[ Q_{Rrev} = c_v (T_1 - T_4) \]

Since,
\[ \left( \frac{T_3}{T_2} \right)^\gamma = \left( \frac{T_4}{T_1} \right) \]

\[ \eta_t = \frac{Q_A + Q_R}{Q_A} = 1 - \left( \frac{1}{\gamma} \right) \left( \frac{T_4 - T_1}{T_3 - T_2} \right) = 1 - \frac{1}{r^{\gamma-1}} \left[ \frac{r^\gamma - 1}{\gamma (r - 1)} \right] \]

\[ r = 25, \quad \eta_t = 0.264 \]

A diesel engine takes in just air, compresses it and then injects fuel into the compressed air. The heat of the compressed air lights the fuel spontaneously.

Note 1: 147000 BTU/gal of Diesel
125000 BTU/gal of Gasoline

Note 2: Diesel is 30 to 35% more efficient than gas powered vehicles, but strongly dependent on vehicle load.

Obert, Internal Combustion Engines, 1970
Fuel Economy of Gasoline & Diesel

Note:
Rudoff Diesel Originally Envisioned Running His Engine on Vegetable Oil

Source: From the fryer to the fuel tank
By Joshua Tickel,

The Volkswagen Jetta with 1.9 liter turbo direct injection Diesel engine gets 50 mpg on the highway.
Alternate Engine Concepts
Turbine Powered Auto’s

1963 Chrysler Turbine

1959 Plymouth Turbine
1964 Chrysler Turbine Car Specifications

• 130 horsepower at 3,600 rpm; 425 lb-ft of torque at zero rpm!
• Weight: 410 lb - 25 inches long, 25.5 inches wide, 27.5 inches tall.
• Fuel requirements: diesel, unleaded gas, kerosene, JP-4, others. No adjustments needed to switch from one to the other.
• Compressor: centrifugal, single-stage compressor with 4:1 pressure ratio, 80% efficiency, 2.2 lb/sec air flow.
• First stage turbine: axial, single-stage, 87% efficiency, inlet temperature 1,700 degrees F.
• Second-stage turbine: axial, single-stage, 84% efficiency, max speed 45,700 rpm.
• Exhaust temperature at full power: 500 °F.
• A 400 °F increase in inlet temperature would mean a 40 per cent increase in specific output improve fuel economy over 20 per cent.
Advantages of Automotive Gas Turbines

- Maintenance is considerably reduced
- Engine life-expectancy is much longer
- The number of parts is reduced 80%
- Tuning-up is almost eliminated
- Low-temperature starting difficulties are eliminated
- No warm-up period is necessary
- Antifreeze is not needed
- Instant heat is available in the winter
- The engine will not stall with sudden overloading
- Engine operation is vibration-free
- Operates on wide variety of fuels
- Oil consumption is negligible
- Engine weight is reduced
- Exhaust gases are hot but clean
- Can be used as a gas generator for electric hybrid.
Issues Associated With Gas Turbines

- High fuel consumption at idle due to high RPM.
- Throttle lag from idle as engine spools up.
- High temperature exhaust gas.
- Very high noise source.
- Expensive parts to replace.
Pistonless Rotary Wankel Engine

Wankel Engine in Deutsches Museum in Munich, Germany

The Good News:
• Wankel has higher power output / unit weight.
• Better fuel/air mixing.
• More even combustion.

The Bad News:
• Rotating seals reduces engine compression ratio.
• Larger fraction of unburned fuel lowers efficiency.
• Excess noise due to rotating seals.

Source: Kevin Reed, Why Wankel Engine is not Famous
Di Pietro Rotary Air Engine

Prototype No. 4

Wheel Power

- Torsion Springs
- Flywheel
- Reverse Mechanism
- Drive Sprocket
- Engine Mounting Support
- Stator
- Compressed Air Inlet
- Distributor Cap
- Distributor

Engine Air Prototype Development

Weight

Power
Engineair’s Ultra-Efficient Rotary Compressed-Air Motor Applications

EngineAir Motor Prototype
Motor Weight: 28.6 Lbs.

Example Products

Note: Each front wheel driven by separate motors
Compressed Air Car

December 2, 2004 French engineers have designed a low consumption and low pollution engine for urban motoring that runs on compressed air technology. The CATS (Compressed Air Technology System) "air car" from Motor Development International is a significant step for zero-emission transport, delivering a compressed air-driven vehicle that is safe, quiet, has a top speed of 110 km/h and a range of 200 km. Costing next to nothing to run, the Zero Emission Vehicle (ZEV) range which includes a pick-up truck and van - is set for release in early 2005.
Air car ready for production

By Bob Ewing  Posted Fri Jul 13, 2007 8:07am PDT

The world's first commercial compressed air-powered vehicle is rolling towards the production line. The Air Car, developed by ex-Formula One engineer Guy Nègre, will be built by India's largest automaker, Tata Motors.

The Air Car uses compressed air to push its engine's pistons. It is anticipated that approximately 6000 Air Cars will be cruising the streets of India by 2008. If the manufacturers have no surprises up their exhaust pipes the car will be practical and reasonably priced. The CityCat model will clock out at 68 mph with a driving range of 125 miles.
Alternate Fuels
## Potential Fuels

<table>
<thead>
<tr>
<th>Energy Sources</th>
<th>Typical Chemical Energy Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>142.0 MJ/kg</td>
</tr>
<tr>
<td>Ethanol</td>
<td>29.7 MJ/kg</td>
</tr>
<tr>
<td>Ammonia</td>
<td>17.0 MJ/kg</td>
</tr>
<tr>
<td>Automotive Gasoline</td>
<td>45.8 MJ/kg</td>
</tr>
<tr>
<td>Methane</td>
<td>55.5 MJ/kg</td>
</tr>
<tr>
<td>Methanol</td>
<td>22.7 MJ/kg</td>
</tr>
</tbody>
</table>

(Source: Chemical Energy, The Physics Hyper text Book)
# Energy Density in Watt-Hour/Liter

<table>
<thead>
<tr>
<th>Material</th>
<th>Volumetric</th>
<th>Gravimetric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel</td>
<td>10942 Wh/l</td>
<td>13762 Wh/kg</td>
</tr>
<tr>
<td>Gasoline</td>
<td>9,700 Wh/l</td>
<td>12,200 Wh/kg</td>
</tr>
<tr>
<td>LNG</td>
<td>7,216 Wh/l</td>
<td>12,100 Wh/kg</td>
</tr>
<tr>
<td>Propane</td>
<td>6,600 Wh/l</td>
<td>13,900 Wh/kg</td>
</tr>
<tr>
<td>Ethanol</td>
<td>6,100 Wh/l</td>
<td>7,850 Wh/kg</td>
</tr>
<tr>
<td>Methanol</td>
<td>4,600 Wh/l</td>
<td>6,400 Wh/kg</td>
</tr>
<tr>
<td>Liquid H2</td>
<td>2600 Wh/l</td>
<td>39,000 Wh/kg</td>
</tr>
<tr>
<td>150 Bar H2</td>
<td>405 Wh/l</td>
<td>39,000 Wh/kg</td>
</tr>
<tr>
<td>Lithium</td>
<td>250 Wh/l</td>
<td>350 Wh/kg</td>
</tr>
<tr>
<td>Nickel Metal Hydride</td>
<td>100 Wh·h/L</td>
<td>60 Wh/kg</td>
</tr>
<tr>
<td>Lead Acid Battery</td>
<td>40 Wh/l</td>
<td>25 Wh/kg</td>
</tr>
<tr>
<td>Compressed Air</td>
<td>17 Wh/l</td>
<td>34 Wh/kg</td>
</tr>
</tbody>
</table>
## Estimates of Alternate Fuel Vehicles In Use

<table>
<thead>
<tr>
<th>Year</th>
<th>LPG</th>
<th>CNG</th>
<th>LNG</th>
<th>M85</th>
<th>M100</th>
<th>E85 b</th>
<th>E95</th>
<th>Electricity</th>
<th>Hydrogen c</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>172,806</td>
<td>50,218</td>
<td>603</td>
<td>18,319</td>
<td>386</td>
<td>1,527</td>
<td>136</td>
<td>2,860</td>
<td>0</td>
<td>246,855</td>
</tr>
<tr>
<td>1996</td>
<td>175,585</td>
<td>60,144</td>
<td>663</td>
<td>20,265</td>
<td>172</td>
<td>4,536</td>
<td>361</td>
<td>3,280</td>
<td>0</td>
<td>265,006</td>
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<tr>
<td>1997</td>
<td>175,679</td>
<td>68,571</td>
<td>813</td>
<td>21,040</td>
<td>172</td>
<td>9,130</td>
<td>347</td>
<td>4,453</td>
<td>0</td>
<td>280,205</td>
</tr>
<tr>
<td>1998</td>
<td>177,183</td>
<td>78,782</td>
<td>1,172</td>
<td>19,648</td>
<td>200</td>
<td>12,788</td>
<td>14</td>
<td>5,243</td>
<td>0</td>
<td>295,030</td>
</tr>
<tr>
<td>1999</td>
<td>178,610</td>
<td>91,267</td>
<td>1,681</td>
<td>18,964</td>
<td>198</td>
<td>24,604</td>
<td>14</td>
<td>6,964</td>
<td>0</td>
<td>322,302</td>
</tr>
<tr>
<td>2000</td>
<td>181,994</td>
<td>100,750</td>
<td>2,090</td>
<td>10,426</td>
<td>0</td>
<td>87,570</td>
<td>4</td>
<td>11,830</td>
<td>0</td>
<td>394,664</td>
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<tr>
<td>2001</td>
<td>185,053</td>
<td>111,851</td>
<td>2,576</td>
<td>7,827</td>
<td>0</td>
<td>100,303</td>
<td>0</td>
<td>17,847</td>
<td>0</td>
<td>425,457</td>
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<tr>
<td>2002</td>
<td>187,680</td>
<td>120,839</td>
<td>2,708</td>
<td>5,873</td>
<td>0</td>
<td>120,951</td>
<td>0</td>
<td>33,047</td>
<td>0</td>
<td>471,098</td>
</tr>
<tr>
<td>2003</td>
<td>190,369</td>
<td>114,406</td>
<td>2,640</td>
<td>0</td>
<td>0</td>
<td>179,090</td>
<td>0</td>
<td>47,485</td>
<td>9</td>
<td>533,999</td>
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<tr>
<td>2004</td>
<td>182,864</td>
<td>118,532</td>
<td>2,717</td>
<td>0</td>
<td>0</td>
<td>211,800</td>
<td>0</td>
<td>49,536</td>
<td>43</td>
<td>565,492</td>
</tr>
<tr>
<td>2005</td>
<td>173,795</td>
<td>117,699</td>
<td>2,748</td>
<td>0</td>
<td>0</td>
<td>246,363</td>
<td>0</td>
<td>51,398</td>
<td>119</td>
<td>592,122</td>
</tr>
</tbody>
</table>

*Average annual percentage change*

1995-2005 0.1% 8.9% 16.4% -10.8% -100% 66.3% -100% 33.5% 9.1%

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*Fuel type abbreviations are used throughout this chapter.*

- **B20** = 20% biodiesel, 80% petroleum diesel
- **CNG** = compressed natural gas
- **E85** = 85% ethanol, 15% gasoline
- **E95** = 95% ethanol, 5% gasoline
- **H₂** = hydrogen
- **LNG** = liquified natural gas
- **LPG** = liquified petroleum gas
- **M85** = 85% methanol, 15% gasoline
- **M100** = 100% methanol
Hydrogen

Issue: Achieve Adequate Stored Energy In An Efficient, Safe and Cost Effective System

<table>
<thead>
<tr>
<th>Hydrogen Storage Technology</th>
<th>Current Volumetric Storage Density (g H₂/L)</th>
<th>Current Gravimetric Storage Density (wt %)</th>
<th>+ of Storage Technology</th>
<th>– of Storage Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000 psi (350 bar)*</td>
<td>~12.5 g H₂/L = 1.5 MJ/L</td>
<td>~2.7 wt%</td>
<td>Known Technology</td>
<td>H₂ under pressure, g H₂/L, Infrastructure, H₂ not humidified</td>
</tr>
<tr>
<td>10000 psi (700 bar)*</td>
<td>~24.2 g H₂/L = 2.9 MJ/L</td>
<td>~3.3 wt%</td>
<td>Known Technology</td>
<td>H₂ under pressure, g H₂/L, Infrastructure, H₂ not humidified</td>
</tr>
<tr>
<td>Liquid*</td>
<td>~37.0 g H₂/L = 4.4 MJ/L</td>
<td>~5.0 wt%</td>
<td>Known Technology</td>
<td>Boil Off, Infrastructure</td>
</tr>
<tr>
<td>Solid Metal Hydrides</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Hydrogen on Demand™ NaBH₄ Chemical Hydride</td>
<td>~&gt; 22 g H₂/L = &gt; 2.5 MJ/L</td>
<td>&gt; 4.0 wt%</td>
<td>H₂ is not under pressure, system design, Infrastructure</td>
<td>Regeneration, Fuel Handling Strategy</td>
</tr>
</tbody>
</table>

Gravimetric storage density: the gravimetric storage density is the weight of the hydrogen being stored divided by the weight of the storage and delivery system proposed.

Source: Oak Ridge National Laboratory Hydrogen Storage Workshop, May 2003
Compressed Gas

Note: Gasoline 13 MJ/L

Pressures > 700 bar
- Stronger, lighter composite tanks (cost)
- Hydrogen permeation
- Non-ideal gas behavior
Gaseous Hydrogen Storage

Work required to compress a gas from Baldur Eliasson and Ulf Bossel:

\[ W = \frac{n}{(n - 1)} P_0 V_0 \left( \frac{P_1}{P_0} \right) \frac{(n-1)}{n} - 1 \]

Hydride storage of hydrogen may be compared to the compression of hydrogen.

Higher Heating value of Hydrogen: 142 MJ/kg
Compressed Gas Cylinders

Carbon fiber wrap/polymer liner tanks are lightweight and commercially available.

<table>
<thead>
<tr>
<th>weight</th>
<th>specific energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 wt.%</td>
<td>7.2 MJ/kg</td>
</tr>
<tr>
<td>7.5 wt.%</td>
<td>9.0 MJ/kg</td>
</tr>
<tr>
<td>10 wt.%</td>
<td>12 MJ/kg</td>
</tr>
</tbody>
</table>

Energy density is the issue:

<table>
<thead>
<tr>
<th>Pressure</th>
<th>Gas density</th>
<th>System density</th>
</tr>
</thead>
<tbody>
<tr>
<td>350 bar</td>
<td>2.7 MJ/L</td>
<td>1.95 MJ/L</td>
</tr>
<tr>
<td>700 bar</td>
<td>4.7 MJ/L</td>
<td>3.4 MJ/L</td>
</tr>
</tbody>
</table>
Liquid Storage - Requires Cryogenic Systems

- Equilibrium temperature at 1 bar for liquid hydrogen is ~20 K.
- Estimated storage densities\(^1\)
  
<table>
<thead>
<tr>
<th>Source</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berry (1998)</td>
<td>4.4 MJ/liter</td>
</tr>
<tr>
<td>Dillon (1997)</td>
<td>4.2 MJ/liter</td>
</tr>
<tr>
<td>Klos (1998)</td>
<td>5.6 MJ/liter</td>
</tr>
</tbody>
</table>

- Issues with this approach are:
  - dormancy.
  - energy cost of liquifaction.

\(^1\) J. Pettersson and O Hjortsberg, KFB-Meddelande 1999:27
High Pressure Cryogenic Tank

Liquid Hydrogen EOS

Estimated energy density: 4.9 MJ/L (Berry 1998)

S. Aceves, et al 2002
Hydrogen Storage - Liquefaction

Total energy requirement for liquefaction of 1 kg of H₂
Hydrogen Delivery Pipelines
Hydrides – Chemically Bond Hydrogen In A Solid Material

- This storage approach should have the highest hydrogen packing density.
- However, the storage media must meet certain requirements:
  - reversible hydrogen uptake/release
  - lightweight with high capacity for hydrogen
  - rapid kinetic properties
  - equilibrium properties (P,T) consistent with near ambient conditions.
- Two solid state approaches
  - hydrogen absorption (bulk hydrogen)
  - hydrogen adsorption (surface hydrogen)
    including cage structures
Alanates

Total hydrogen content of some alanates

- LiAIH₄
- NaAIH₄
- KAIH₄
- Be(AIH₄)₂
- Na₂LiAIH₆
- Mg(AIH₄)₂
- CuAIH₄
- Ca(AIH₄)₂
- Mn(AIH₄)₂
- Fe(AIH₄)₂
- AgAIH₄
- Ti(AIH₄)₃
- Ga(AIH₄)₃
- CsAIH₄
- Ti(AIH₄)₄
- In(AIH₄)₃
- Zr(AIH₄)₄
- Ce(AIH₄)₃
- Sn(AIH₄)₄

Increasing mol. weight

Weight percent hydrogen
## Complex Hydrides

### Chemical Hydrides – H₂ Generation by Hydrolysis

<table>
<thead>
<tr>
<th>Reaction</th>
<th>wt% H₂</th>
<th>Capacity, kWh/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiH + H₂O → LiOH + H₂</td>
<td>7.7</td>
<td>1.46</td>
</tr>
<tr>
<td>NaH + H₂O → NaOH + H₂</td>
<td>4.8</td>
<td>0.91</td>
</tr>
<tr>
<td>CaH₂ + 2 H₂O → Ca(OH)₂ + 2 H₂</td>
<td>5.2</td>
<td>0.99</td>
</tr>
<tr>
<td>LiAlH₄ + 4 H₂O → LiOH + Al(OH)₃ + 4 H₂</td>
<td>7.3</td>
<td>1.38</td>
</tr>
<tr>
<td>LiBH₄ + 4 H₂O → LiOH + H₃BO₃ + 4 H₂</td>
<td>8.6</td>
<td>1.63</td>
</tr>
<tr>
<td>NaAlH₄ + 4 H₂O → NaOH + Al(OH)₃ + 4 H₂</td>
<td>6.4</td>
<td>1.21</td>
</tr>
<tr>
<td>NaBH₄ + 4 H₂O → NaOH + H₃BO₃ + 4 H₂</td>
<td>7.3</td>
<td>1.38</td>
</tr>
</tbody>
</table>
Storage Methods

Hydrogen storage methods

Excluding ancillaries

Theoretical capacity (wt %)

Theoretical capacity (Wh/kg)

Steel cylinder
Composite cylinder
Secondary hydrides
Liquid hydrogen
Primary hydrides hydrolisis
Silanes
LiAlH₄ + NH₄Cl Thermal decomp.
NH₃BH₃ Thermal decomp.
Carbon nanofibres
Improvements

Path to Improvement

Improving storage capacity will require improvement in material performance that will also enable a better system design.

- Better advanced storage materials are needed that will have:
  - Lower weight
  - Smaller volume
  - Lower cost
  - Better stability

- Additional material requirements must be met to allow improvement in system-level characteristics:
  - Low energy use for hydrogen liberation
  - Easy and energy efficient “recharging” or recycling
  - Low-temperature and pressure operation

- Achieving the necessary improvements will require:
  - A solid understanding of the fundamentals of hydrogen storage
  - Invention
  - Solid experimentation
# US DOE Targets

**DOE Technical Targets: On-Board Hydrogen Storage**

<table>
<thead>
<tr>
<th>_aspect</th>
<th>Units</th>
<th>Target</th>
<th>Status Physical Storage</th>
<th>Status Chemical Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage Weight Percent</td>
<td>%</td>
<td>6</td>
<td>5.2</td>
<td>3.4</td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td>%</td>
<td>97</td>
<td>94</td>
<td>88</td>
</tr>
<tr>
<td>Energy Density</td>
<td>W-h/L</td>
<td>1100</td>
<td>800</td>
<td>1300</td>
</tr>
<tr>
<td>Specific Energy</td>
<td>W-h/kg</td>
<td>2000</td>
<td>1745</td>
<td>1080</td>
</tr>
<tr>
<td>Cost</td>
<td>$/kW-h</td>
<td>5</td>
<td>50</td>
<td>18</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>ºC</td>
<td>-40–50°C</td>
<td>-40–50°C</td>
<td>-20–50°C</td>
</tr>
<tr>
<td>Start-Up Time To Full Flow</td>
<td>sec</td>
<td>15</td>
<td>&lt;1</td>
<td>&lt;15</td>
</tr>
<tr>
<td>Hydrogen Loss</td>
<td>scc/hr/L</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Cycle Life</td>
<td>Cycles</td>
<td>500</td>
<td>&gt;500</td>
<td>20–50</td>
</tr>
<tr>
<td>Refueling Time</td>
<td>min</td>
<td>&lt;5</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Recoverable Usable Amount</td>
<td>%</td>
<td>90</td>
<td>99.7</td>
<td>&gt;90</td>
</tr>
</tbody>
</table>
Flex Fuels

- Flexible fuel vehicles (FFVs) are designed to run on gasoline or a blend of up to 85% ethanol (E85). Except for a few engine and fuel system modifications, they are identical to gasoline-only models.
- FFVs have been produced since the 1980s, and dozens of models are currently available. Since FFVs look just like gasoline-only models, you may have an FFV and not even know it. To determine if your vehicle is an FFV, check the inside of your car's fuel filler door for an identification sticker or consult your owner's manual.
- FFVs experience no loss in performance when operating on E85. However, since a gallon of ethanol contains less energy than a gallon of gasoline, FFVs typically get about 20-30% fewer miles per gallon when fueled with E85.
Ethanol Production

Million Gallons Per Year

<table>
<thead>
<tr>
<th>Country</th>
<th>2004</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S.</td>
<td>3,535</td>
<td>4,264</td>
</tr>
<tr>
<td>Brazil</td>
<td>3,989</td>
<td>4,227</td>
</tr>
<tr>
<td>China</td>
<td>964</td>
<td>1,004</td>
</tr>
<tr>
<td>India</td>
<td>462</td>
<td>449</td>
</tr>
<tr>
<td>France</td>
<td>219</td>
<td>240</td>
</tr>
<tr>
<td>Russia</td>
<td>198</td>
<td>198</td>
</tr>
<tr>
<td>South Africa</td>
<td>110</td>
<td>103</td>
</tr>
<tr>
<td>U.K.</td>
<td>106</td>
<td>92</td>
</tr>
<tr>
<td>Others</td>
<td>1,187</td>
<td>1,573</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>10,770</td>
<td>12,150</td>
</tr>
</tbody>
</table>

States in US with Ethanol Plants (2006): 21

>1.4 billion bushels of corn used in US for ethanol, 13-16% of US corn crop. Also used 15% of grain sorghum crop. 18% of corn crop projected by 2010. 10% ethanol blend nationally would require 50% of current corn crop (5 billion bushels)

9 million metric tons of distillers grains

Ethanol Plant Energy Consumption
Ethanol Plant Water Consumption

It would take 1,215 gallons of water per acre of corn for the conversion process. The yield per acre of corn to ethanol is 405 gallons. That’s per year. So how much would it take to run our country for just one day on ethanol? Here are the numbers, 32,035,500 gallons of ethanol or 791,000 acres of corn, 96,106,500 gallons of water and that is just to process it to ethanol. We still have not touched the amount of water it takes to grow it. So for the yearly amount of water required for an ethanol only market is 34,982,766,000. 35 BILLION gallons of water!

Water use by Ethanol plants, Institute for Agriculture and Trade Policy, Minnesota 2006.
Emission Test Results From Aftermarket Conversions

Washington, D.C.: CNG Conversion Vehicles — Kit make: GFI

<table>
<thead>
<tr>
<th>Vehicle Model</th>
<th>Model Year</th>
<th>Before Conversion (RFG)</th>
<th>After Conversion (RFG)</th>
<th>After Conversion (CNG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acclaim</td>
<td>1992</td>
<td>0.23 4.13 0.15</td>
<td>NC</td>
<td>0.0</td>
</tr>
<tr>
<td>Acclaim</td>
<td>1992</td>
<td>0.46 3.52 0.11</td>
<td>NC</td>
<td>0.0</td>
</tr>
<tr>
<td>Astro</td>
<td>1992</td>
<td>1.01 2.42 0.48</td>
<td>NC</td>
<td>0.0</td>
</tr>
<tr>
<td>Caravan</td>
<td>1992</td>
<td>0.75 1.30 0.23</td>
<td>0.00</td>
<td>0.0</td>
</tr>
<tr>
<td>Caravan</td>
<td>1992</td>
<td>0.53 1.96 0.24</td>
<td>NC</td>
<td>0.0</td>
</tr>
<tr>
<td>Safari</td>
<td>1993</td>
<td>1.14 4.92 0.46</td>
<td>NC</td>
<td>0.0</td>
</tr>
<tr>
<td>Safari</td>
<td>1993</td>
<td>1.20 6.19 0.54</td>
<td>NC</td>
<td>0.0</td>
</tr>
<tr>
<td>Taurus</td>
<td>1994</td>
<td>0.22 1.08 0.09</td>
<td>NC</td>
<td>0.0</td>
</tr>
<tr>
<td>Taurus</td>
<td>1994</td>
<td>0.17 0.98 0.08</td>
<td>NC</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Denver CNG Conversion Vehicles — Kit make: GFI

<table>
<thead>
<tr>
<th>Vehicle Model</th>
<th>Model Year</th>
<th>Before Conversion (RFG)</th>
<th>After Conversion (RFG)</th>
<th>After Conversion (CNG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B250</td>
<td>1994</td>
<td>2.31 8.66 0.84</td>
<td>NC</td>
<td>0.0</td>
</tr>
<tr>
<td>B250</td>
<td>1994</td>
<td>0.65 2.75 0.16</td>
<td>0.00</td>
<td>0.0</td>
</tr>
<tr>
<td>C1500</td>
<td>1994</td>
<td>0.49 2.88 0.17</td>
<td>NC</td>
<td>0.0</td>
</tr>
<tr>
<td>C1500</td>
<td>1994</td>
<td>0.61 3.98 0.18</td>
<td>NC</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Denver LPG Conversion Vehicles — Kit make and model: IMPCO ADP

<table>
<thead>
<tr>
<th>Vehicle Model</th>
<th>Model Year</th>
<th>Before Conversion (RFG)</th>
<th>After Conversion (RFG)</th>
<th>After Conversion (LPG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F150 pkup</td>
<td>1994</td>
<td>1.20 0.66 0.09</td>
<td>0.00</td>
<td>0.0</td>
</tr>
<tr>
<td>F150 pkup</td>
<td>1994</td>
<td>0.88 0.80 0.08</td>
<td>0.00</td>
<td>0.0</td>
</tr>
<tr>
<td>Taurus</td>
<td>1994</td>
<td>0.25 0.80 0.09</td>
<td>0.00</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Source: NREL

- Large emissions decrease (>50%)
- Moderate emissions increase (10%-50%)
- Moderate emissions decrease (10%-50%)
- Large emissions increase (>50%)
- NC = No change (i.e., less than 10%)
Combination of biomass gasification (BG) and Fischer-Tropsch (FT) synthesis is a possible route to produce renewable transportation fuels (biofuels).

Fischer-Tropsch Used to Form Alkenes
With Either Iron or Cobalt as Catalysts

\[(2n + 1)H_2 + nCO \rightarrow C_nH_{(2n+2)} + nH_2O\]
## Biofuel Classification

<table>
<thead>
<tr>
<th>PRODUCTION SIDE, SUPPLY</th>
<th>MAJOR COMMODITIES</th>
<th>USER SIDE, DEMAND EXAMPLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Woodfuels</td>
<td><strong>WOODFUELS</strong></td>
<td>Solid: Fuelwood (wood in the rough, chips, sawdust, pellets), Charcoal</td>
</tr>
<tr>
<td>Indirect Woodfuels</td>
<td></td>
<td>Liquid: Black liquor, Methanol, Pyrolytic oil</td>
</tr>
<tr>
<td>Recovered Woodfuels</td>
<td></td>
<td>Gases: Products from gasification and pyrolysis gases of above fuels</td>
</tr>
<tr>
<td>Fuel crops</td>
<td><strong>AGROFUELS</strong></td>
<td>Solid: Straw, Stalks, Husks, Charcoal from agrofuels</td>
</tr>
<tr>
<td>Agricultural by-products</td>
<td></td>
<td>Liquid: Ethanol, Raw vegetable oil, Oil diester, Methanol, Pyrolytic oil</td>
</tr>
<tr>
<td>Animal by-products</td>
<td></td>
<td>Gases: Biogas, Producer gas, Pyrolysis gases from agrofuels</td>
</tr>
<tr>
<td>Agroindustrial by-products</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Municipal by-products</td>
<td><strong>MUNICIPAL BY-PRODUCTS</strong></td>
<td>Solid: Municipal solid wastes (MSW)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Liquid: Sewage sludge, Pyrolytic oil from MSW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gases: Landfill gas, Sludge gas</td>
</tr>
</tbody>
</table>

# Oil Crop Production

<table>
<thead>
<tr>
<th>Plant</th>
<th>Latin Name</th>
<th>lb. oil/acre</th>
<th>kg. oil/hectare</th>
</tr>
</thead>
<tbody>
<tr>
<td>oil palm</td>
<td>Elaeis guineensis</td>
<td>4,585</td>
<td>5,000</td>
</tr>
<tr>
<td>coconut</td>
<td>Cocos nucifera</td>
<td>2,070</td>
<td>2,260</td>
</tr>
<tr>
<td>jatropha</td>
<td>Jatropha curcas</td>
<td>1,460</td>
<td>1,590</td>
</tr>
<tr>
<td>rapeseed</td>
<td>Brassica napus</td>
<td>915</td>
<td>1,000</td>
</tr>
<tr>
<td>peanut</td>
<td>Arachis hypogaea</td>
<td>815</td>
<td>890</td>
</tr>
<tr>
<td>sunflower</td>
<td>Helianthus annuus</td>
<td>720</td>
<td>800</td>
</tr>
<tr>
<td>safflower</td>
<td>Carthamus tinctorius</td>
<td>605</td>
<td>655</td>
</tr>
<tr>
<td>soybean</td>
<td>Glycine max</td>
<td>345</td>
<td>375</td>
</tr>
<tr>
<td>hemp</td>
<td>Cannabis sativa</td>
<td>280</td>
<td>305</td>
</tr>
<tr>
<td>corn</td>
<td>Zea mays</td>
<td>135</td>
<td>145</td>
</tr>
</tbody>
</table>

Figures are international averages. Harvests vary with region and sub-species.

# Fuel Crops

<table>
<thead>
<tr>
<th>Crop</th>
<th>Fuel (GJ/acre)</th>
<th>Protein (kg/acre)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soybeans</td>
<td>7.7</td>
<td>393</td>
</tr>
<tr>
<td>Corn</td>
<td>39</td>
<td>457</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>95</td>
<td>400</td>
</tr>
</tbody>
</table>

- Soybeans: 38 wt% protein, 20 wt% oil, 38 bu/acre
- Corn: 10 wt% protein, 2.7 gal/bu, 180 bu/acre
- Switchgrass: 4 wt% protein, 117 gal/ton, 10 ton/acre
## Biodiesel Vs. Petroleum Based Diesel

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domestically produced from non-petroleum, renewable resources</td>
<td>Use of blends above B5 not yet warrantied by auto makers</td>
</tr>
<tr>
<td>Can be used in most diesel engines, especially newer ones</td>
<td>Lower fuel economy and power (10% lower for B100, 2% for B20)</td>
</tr>
<tr>
<td>Less air pollutants (other than nitrogen oxides) and greenhouse gases</td>
<td>Currently more expensive</td>
</tr>
<tr>
<td>Biodegradable</td>
<td>More nitrogen oxide emissions</td>
</tr>
<tr>
<td>Non-toxic</td>
<td>B100 generally not suitable for use in low temperatures</td>
</tr>
<tr>
<td>Safer to handle</td>
<td>Concerns about B100's impact on engine durability</td>
</tr>
</tbody>
</table>

**Notes:** Diesel Engine is 30-35% More Fuel Efficient Than Similar Sizes Gasoline Engine.

Ultra Low Sulfur Diesel (ULSD) lowers particulates and combats NOx emissions.

All figures cited were originally gathered and reported by www.fueleconomy.gov
Biodiesel vs Diesel Emissions

Outlook for Biofuels

Share of Biofuels in Road-Transport Fuel Demand

Dr. Roberto Schaeffer, Climate Change in Brazil, UNDESA, Nov. 2007
Biofuels Supply Costs

Significant production cost reductions are expected especially for 2nd – generation ligno-cellulusic ethanol.

Dr. Roberto Schaeffer, Climate Change in Brazil, UNDESA, Nov. 2007
Production Costs and Prices

- Electricity: $0.05/kWh to $0.15/kWh
- Diesel Fuel: $1/gal to $3/gal
- Petroleum: $10/bbl to $70/bbl
- Solid Fuel: $?
- DME: $?
- H2: $?
- Syngas: $?
- Bio-oil: $?
- BTL: $?
- Biogas: $?
- Biodiesel: $?
- Methanol: $?
- Ethanol: $?
Alternate Power Sources
Fuel Cells

Costs:
In 2002, typical cells had a catalyst content of US$1000 per kilowatt of electric power output. In 2008 UTC Power has 400kw Fuel cells for $1,000,000 per 400kW installed costs. The goal is to reduce the cost in order to compete with current market technologies including gasoline internal combustion engines.
Honda FCX Clarity

Hydrogen Fuel Port
Fuel Cell Electric Vehicle Storage System

Comparative Volumes andWeights of a FCEV Hydrogen Storage System
(Capable of 560 km (350 mi) Range – Compact Sedan)

![Graph showing comparative volumes and weights of different hydrogen storage methods.](image)
Storage Systems

<table>
<thead>
<tr>
<th></th>
<th>System Weight</th>
<th>System Volume</th>
<th>Extraction Complexity</th>
<th>System Cost</th>
<th>Fuel Cost</th>
<th>Dormancy</th>
<th>Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressed Gas (5,000 psi)</td>
<td>Good</td>
<td>Acceptable</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Cryogenic Liquid H2</td>
<td>Good</td>
<td>Acceptable</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Cryo - Liquid Compressed H2</td>
<td>Good</td>
<td>Acceptable</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Rechargeable Metal Hydride</td>
<td>Problem</td>
<td>Acceptable</td>
<td>Problem</td>
<td>Problem</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Chemical Hydride</td>
<td>Acceptable</td>
<td>Good</td>
<td>Acceptable</td>
<td>Acceptable</td>
<td>Acceptable</td>
<td>Acceptable</td>
<td>Acceptable</td>
</tr>
</tbody>
</table>

Green: Good  Yellow: Acceptable  Red: Problem
Hybrids

Hybrid Features:
• Regenerative braking
• Electric motor drive/assist
• Automatic start/shutoff
• Great gas mileage

Source: Alternate Fuel Vehicle
# Available & Planned Hybrids

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>Type</th>
<th>Available</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chrysler</td>
<td>Aspen HEMI Hybrid</td>
<td>SUV</td>
<td>2008</td>
</tr>
<tr>
<td>Dodge</td>
<td>Durango HEMI Hybrid</td>
<td>SUV</td>
<td>2008</td>
</tr>
<tr>
<td>Ford</td>
<td>Fusion Hybrid</td>
<td>Midsize Car</td>
<td>2008</td>
</tr>
<tr>
<td>Mercury</td>
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<td>Midsize Car</td>
<td>2008</td>
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<td>SUV</td>
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<td>Five Hundred Hybrid</td>
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<td>2008-10</td>
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<td>ML450 Hybrid</td>
<td>SUV</td>
<td>2009</td>
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<td>S400 BlueHybrid</td>
<td>Large Car</td>
<td>2009-10</td>
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<td>X6</td>
<td>SUV</td>
<td>2010</td>
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<td>SUV</td>
<td>2010</td>
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<tr>
<td>Honda</td>
<td>Fit Hybrid</td>
<td>Small Station Wagon</td>
<td>2010-15</td>
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Three new hybrids for 2009
- Cadillac Escalade Hybrid
- Chevrolet Silverado 15 Hybrid
- GMC Sierra 15 Hybrid

All Electric Tesla Car
Well To Wheel Energy Pathways

Battery Electric Vehicle

- 79 kWh from renewable source
- Power lines 92% effic.
- Battery charger 89% effic.
- Li-ion batteries 94% effic.
- Electric drivetrain 89% effic.

Fuel Cell Vehicle

- 202 kWh from renewable source
- Electrolysis 72% effic.
- H₂ gas pipeline* 86% effic.
- H₂ storage 54% effic.
- Fuel cell sys. 89% effic.
- Electric drivetrain 89% effic.
- 60 kWh to wheels

Factors Affecting New Airplane Launch Decisions

- **Economics - International Market Competition**
  - Aircraft Cost/Efficiency/Productivity
  - Airport Gate / Runway Productivity

- **Additional Constraints**
  - Energy Efficiency
  - Emissions
  - Noise
  - Safety
Factors Influencing Airplane Ticket Price
5500 Nautical Mile Stage Length

Diagram showing the factors affecting airplane ticket prices with a focus on 5500 nautical mile stage length.
Blended Wing Body Concept

Benefits:
- 20-25 % Less Fuel
- 10-15% Less Weight
- 10-15% Lower DOC

Challenges:
- Propulsion/Airframe Integration
- Aero-Structural Integration
- Aerodynamics
- Controls
Subsonic Aircraft Comparison
5500 Nautical Mile Stage Length

- 0.65 LOAD FACTOR
- M=0.85
- 412 SEATS
- 800 SEATS
- L/D=17.5
- L/D=21.2
- L/D=24
- L/D=33

FARE IN $/PASS N.M.
Estimated Fuel Economy

Aircraft type

Seat
n.m./gallon

B747-400  ADV TURB  ADV LAM  BWB