Engineering Distinguished Lecture Series

California’s Clean Transportation Future
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Jeffrey Reed
Director of Emerging Technologies
SoCalGas / SDG&E
Macro View

What we know

- Vehicles will be 50% up to more energy efficient in 15 years
- There will be millions of alternative fuel vehicles on the road within 10 years
- A single technology “winner” is unlikely for either light duty or heavy duty applications
- Large amounts of money will be made and lost seeking the pot at the end of the rainbow

What we don’t know

- The precise path the market(s) will take
- What technical breakthroughs will occur and when
What Makes a Market?

- Vehicle Choice
- Convenient Fueling
- Reasonable Prices
- Consumer Confidence
History Shows that Rapid Adoption Can Happen if the “Triangle” is Complete

It took about 12 years for the car to replace the horse

U.S. Hybrid Electric Vehicle Sales
1 Million Cumulative in 8 Years

Global NGV Use
~15 million worldwide

Natural Gas Vehicles (millions)

- Asia Pacific
- Europe
- North America
- Latin America

Positive Signal – Manufacturers are Offering Growing Array of Choices

- Plug-In Hybrids
- Fuel Cell Vehicles
- Battery Electric Vehicles

Natural Gas Vehicles
Detroit Needs to Work Its Magic on Cost

Current FCHV (2008)

- Body, chassis, hybrid system components, etc.

Next Generation FCHV

Future cost reduction potential

Demonstration phase

FC vehicle cost

2011 Status

2015 Initial market entry

Growth phase market expansion
Public Fueling Infrastructure is Currently a Weak Link

Public Fueling Locations in the U.S.

<table>
<thead>
<tr>
<th>Location</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>9</td>
</tr>
<tr>
<td>LNG</td>
<td>29</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>287</td>
</tr>
<tr>
<td>CNG</td>
<td>527</td>
</tr>
<tr>
<td>Ethanol</td>
<td>2,270</td>
</tr>
<tr>
<td>Electric</td>
<td>4,688</td>
</tr>
<tr>
<td>Gasoline</td>
<td>150,000</td>
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</tbody>
</table>
Opportunity -- Integration and Synergy with Existing Infrastructure

- Potential to use batteries during or at end of vehicle life for grid storage
- Smart Charging to maximize utilization of the electric grid
- Use of existing natural gas infrastructure to deliver biomethane and/or hydrogen blends
Which Solution(s) Will Win?

- Electric and hybrid electric drive
- Hydrogen fuel cell vehicles
- Natural gas vehicles
- Biofuels (liquid and gaseous)

Depends on:
- Emission characteristics and requirements
- Ultimate cost per mile = Combination of vehicle and fuel cost
- Vehicle “vocation”: size, miles traveled and performance requirements (like load pulling or hills)
## Costs and Emissions as of 2010

<table>
<thead>
<tr>
<th>Technologies</th>
<th>NOx (g/mi) (tailpipe)</th>
<th>GHG (g/mi) (WTW)</th>
<th>Cost per ton NOx reduced</th>
<th>Cost per ton GHG reduced</th>
<th>Total cost per mile</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010 CNG</td>
<td>0.8</td>
<td>2,607</td>
<td>n/a</td>
<td>($590)</td>
<td>$1.56</td>
</tr>
<tr>
<td>CNG with advanced after-treatment</td>
<td>0.12</td>
<td>2,607</td>
<td>($536K)</td>
<td>($540)</td>
<td>$1.60</td>
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<tr>
<td>H/CNG</td>
<td>0.8</td>
<td>2,688</td>
<td>n/a</td>
<td>($393)</td>
<td>$1.74</td>
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<tr>
<td>Renewable NG</td>
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<td>435</td>
<td>n/a</td>
<td>($52)</td>
<td>$1.80</td>
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<tr>
<td>CNG hybrid</td>
<td>0.6</td>
<td>1,955</td>
<td>($705K)</td>
<td>($106)</td>
<td>$1.85</td>
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<tr>
<td>2010 Diesel - baseline</td>
<td>0.8</td>
<td>3,282</td>
<td>n/a</td>
<td>n/a</td>
<td>$2.00</td>
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<tr>
<td>Diesel hybrid</td>
<td>0.6</td>
<td>2,462</td>
<td>$675K</td>
<td>$164</td>
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<tr>
<td>Battery electric</td>
<td>0.0</td>
<td>1,593</td>
<td>$1.1M</td>
<td>$500</td>
<td>$2.93</td>
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<tr>
<td>Fuel cell</td>
<td>0.0</td>
<td>1,793</td>
<td>$4.7M</td>
<td>$2,539</td>
<td>$6.17</td>
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</table>

Source: Gladstein, Neandross and Associates
Note: Emissions are in comparison to 2010 compliant diesel bus
Good News -- Lots of Common Technology Opportunities

### Source: CARB Clean Car Program presentation
Example – Low-Pressure Adsorption Storage for Natural Gas or Hydrogen

- Micro or nano-structured carbon adsorbent lowers the pressure required to store gaseous fuel

- Benefits = less expensive tanks with more flexibility on shape (and location)
What’s Needed

- Private capital investment (VC’s, auto manufacturers, etc.) – which requires clear and stable public policy and regulation

- Continued public investment in RD&D (DoE programs are yielding great results)

- Well designed, performance-based incentives (with a “graduation plan”) where needed to jump start markets – with consideration of both infrastructure and vehicles
What’s the Prize?

- Clean Air
- Rejuvenation of American manufacturing
- Freedom from dependence on foreign energy
- Great, interesting jobs for engineers
- $3.8 trillion in net present value (according to Amory B. Lovins in his recent book Reinventing Fire)