The Next Generation
Near-Zero Emission Natural Gas Vehicles

Jeff Reed
Director of Emerging Technologies
Southern California Gas Company
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Context

Natural gas is
- Clean
- Cost effective
- Domestic

However – emission standards are getting tighter and tighter

Key question – how close can natural gas get to zero emissions and at what cost?
NGV Technology Advances will be Key

<table>
<thead>
<tr>
<th>Opportunity Area</th>
<th>Comments</th>
</tr>
</thead>
</table>
| Engine Technology and Drive Trains| • Improvements of 35% to 60%+ in fuel economy predicted by some experts  
• Both engine technology and hybridization can help  
• Aerodynamics, light-weight materials and peripherals can help as well  
• Fuel efficiency eliminates all tailpipe emissions -- #1 in the “loading order” |
| Advanced After-treatment          | • Catalyst systems similar to those in use today  
• Has technical potential to reduce NOx to “near zero” levels (90% less than 2010 standards)                                                                                                           |
| Carbon – the elephant in the room | • Biogas  
• Solar methane synthesis                                                                                                                                                                                |
| “Supporting “ advances  
-- On-board tanks  
-- Fueling infrastructure | • Helps reduce lifecycle emissions by reducing required compression energy  
• Low–cost, efficient fueling infrastructure is a key enabler  
• Efficiency improvements reduce lifecycle emissions                                                                                                                                                   |
Objective
Develop dedicated natural gas engine with near zero emissions without sacrificing performance or efficiency compared to 2010 diesel engine

Demonstration Elements
• Modify 11L 340hp Doosan engine (conversion from lean burn SCR)
• Stoichiometric operation
• Cooled Exhaust Gas Recirculation for mixture dilution
• Three way Catalyst
• Advanced ignition system for highly dilute mixtures
• Optimized in-cylinder turbulence
• High efficiency turbo matching
• Advanced control for knock and misfire detection

Expected Benefits:
• 80% reduction in NOx emissions
• Replace SCR with 3-way catalyst
• Similar efficiency and cost to diesel alternatives
Objective
Develop a near zero emissions dual liquid / natural gas combustor for the existing 350 kW gas turbine engine designed for Class-8 trucks.

Benefits
- Near-zero emissions (90% NOx improvement)
- Fuel flexibility
- Improved efficiency through hybridization
**Biogas = Lowest GHG Vehicle Fuel Pathway**

**Greenhouse Gas Emissions Comparison Across Fuels**

*2020 Target GHG Level*
- Gasoline 86, Diesel 85 (10% reduction)

**Well-to-Wheels (WTW) GHG Emissions (gCO2e/MJ)**

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Well-to-Wheels (WTW) Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>97</td>
</tr>
<tr>
<td>Diesel</td>
<td>95</td>
</tr>
<tr>
<td>Ethanol (Corn)</td>
<td>99</td>
</tr>
<tr>
<td>Ethanol (Sgrcane)</td>
<td>72</td>
</tr>
<tr>
<td>Hydrogen (SMR NG)</td>
<td>59</td>
</tr>
<tr>
<td>Electricity (CA Avg)</td>
<td>41</td>
</tr>
<tr>
<td>Biodiesel (Soy)</td>
<td>27</td>
</tr>
<tr>
<td>Ethanol (Cellulosic)</td>
<td>23</td>
</tr>
<tr>
<td>CNG</td>
<td>74</td>
</tr>
<tr>
<td>LF CNG</td>
<td>12</td>
</tr>
</tbody>
</table>

*Negative WTT emissions for LF CNG are due to a carbon credit issued to landfills for capturing methane instead of flaring*

NGVs provide significant carbon reductions

Bio-Methane is the lowest carbon transportation fuel available

**Source:** CARB
SoCalGas commissioned analysis to assess performance and cost effectiveness of various natural gas solutions for transit buses.

- **Baseline technologies**
  - Model year 2010 diesel or natural gas engines (0.2 g/bhp-hr NOx)
  - Hydrogen hybrid-electric fuel cell
  - Battery electric

- **Fuel alternatives for a “zero emission” bus**
  - Natural gas with advanced after-treatment
  - Natural gas hybrid-electric
  - Renewable CNG
  - Hydrogen-natural gas blended fuels

Three-way catalyst system
## Analysis Results

<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>
</tr>
<tr>
<td>H/CNG</td>
<td>0.8</td>
<td>2,688</td>
<td>n/a</td>
<td>($393)</td>
<td>$1.74</td>
</tr>
<tr>
<td>Renewable NG</td>
<td>0.8</td>
<td>435</td>
<td>n/a</td>
<td>($52)</td>
<td>$1.80</td>
</tr>
<tr>
<td>CNG hybrid</td>
<td>0.6</td>
<td>1,955</td>
<td>($705K)</td>
<td>($106)</td>
<td>$1.85</td>
</tr>
<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>
</tr>
<tr>
<td>Diesel hybrid</td>
<td>0.6</td>
<td>2,462</td>
<td>$675K</td>
<td>$164</td>
<td>$2.15</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>
</tr>
<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>
</tr>
</tbody>
</table>
Advanced Storage Systems

- Advanced cost effective CNG and LNG on-board fuel storage systems
  - Adsorbed Natural Gas, new materials
  - Conformable Tank Configurations
  - Extended Cylinder Certification Life
  - Non-destructive Active Monitoring for Damage Detection
  - Nitrogen Blanketed/No Vent Cryogenic Tank Technology

A 120-gallon LNG tank is mounted under the cab.
Objective
Reduce compression requirement for on-board natural gas fuel storage at comparable energy density (volume requirement

Benefits:
• Less-expensive, thinner-walled pressure vessels
• Conformability
• Less-compression
Example – Next-gen CNG Infrastructure

Objective:
The project is demonstration of three self-contained CNG compressor units manufactured by GNC Galileo S.A., of Argentina for fleet and retail applications

Potential benefits over traditional CNG compressors:
• Compact, self-contained unit suitable for urban setting
• Plug and Play - all components in explosion proof steel enclosure
• Ability to right size a fast-fill product to demand
• Provide solution for small and mid-sized fleets
• Smart software to optimize performance and diagnose problems quickly

Market development objectives:
• Full commercial availability of cost-effective solution for small and mid-sized fleets
• Create customer pull for other competitive products
Example -- Home Refueling Appliance

- Goal: Facilitate the design and manufacture of ‘next generation’ CNG fueling appliance(s) approved for residential use.

- Product Targets: Fuel cost adder of $1/gal or less

- Potential Vendors/Manufacturers: over 25 identified to date

- Overall goal is to facilitate introduction of cost-effective products by 2013
CNG More Economical for Many Segments Today

Heavy-Duty Vehicles

<table>
<thead>
<tr>
<th></th>
<th>Transit</th>
<th>Refuse</th>
<th>Goods Movement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel Baseline</td>
<td>$2.00</td>
<td>$3.50</td>
<td>$1.50</td>
</tr>
<tr>
<td>Diesel Hybrid</td>
<td>$1.50</td>
<td>$3.00</td>
<td>$1.00</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>$1.00</td>
<td>$2.50</td>
<td>$0.50</td>
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- $ per mile
- Fuel Cost
- Maintenance Cost
- Vehicle Cost

**Legend:**
- Blue: Fuel Cost
- Maroon: Maintenance Cost
- Yellow: Vehicle Cost
Economics – Passenger NGV can be Cheaper than Conventional

**Current U.S Gasoline vs. NGV**

<table>
<thead>
<tr>
<th>2012 Civic LX (Gasoline)</th>
<th>Purchase price uplift</th>
<th>Maintenance uplift</th>
<th>Fuel cost savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>$31,424</td>
<td>$8,300</td>
<td>$1,317</td>
<td>$4,356</td>
</tr>
<tr>
<td>$36,685</td>
<td></td>
<td></td>
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**Potential Gasoline vs. NGV**

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<tr>
<td>$34,687</td>
<td>$4,150</td>
<td>$1,317</td>
<td>$7,619</td>
</tr>
<tr>
<td>Hi volume Civic NGV</td>
<td></td>
<td></td>
<td>$32,535</td>
</tr>
</tbody>
</table>

Assumptions:
- Current Honda Civic CNG vehicle price
- Cost difference reduced by 50% with high volume production (similar to current differential in Italy)
- Current fuel price $3.85 per gallon; alternative case gasoline price $5.00
- CNG price $2.30 per gasoline gallon equivalent
- 15,000 miles per year at 29 mpg
Conclusions

- Natural Gas Vehicle technology is advancing at a fast pace
- Emissions challenges are significant but solutions are in sight to meet long-term goals
- Low-cost, domestic fuel is a major advantage