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Natural Gas and Transportation

Options for Effective Resource Management

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Potential for NG as a Vehicle Fuel

Five Primary Options to Use NG for Transportation

- Compressed Natural Gas (CNG) Vehicles
  - Light and heavy-duty applicable
- Liquefied Natural Gas (LNG) Vehicles
  - Heavy-duty directly applicable, LD infrastructure
- Electric Generation using NG + Electric Vehicles
  - Trolley buses as opposed to battery electric
- NG Conversion to Synthetic Diesel Fuel
  - Minimize evaporative loss emissions
- NG as Fuel Stock for Hydrogen Fuel Cell

Biggest issue with each option is the infrastructure required to transport Fuel (or energy) from well-head to vehicle

Non-Transportation NG Opportunities

Optimize NG Usage in Multiple Markets to Match Overall Patterns of Energy Use

- Electric Generating and Manufacturing
  - Can utilize same infrastructure as transportation
  - Maximize capital utilization to recover capital costs faster
- Opportunity for export products (LNG, Synthetic Diesel)
  - LNG manufacture can also be used to manage gas quality
  - Synthetic Diesel for export and domestic demonstrations
- Residential Heating and Cooking Uses
  - Gas quality for residential uses is not as high as that necessary for transportation uses and blending to extend supply can negatively impact transportation users

Evaluation Metrics

What is the Preferred Performance Metric?

- Fuel Economy – km/liter (liter/100km)
- Energy Economy - km/therm (therm/100km)
- Cost-Effectiveness – cost/therm vs. Price/therm
  - Available tax revenue from different options
  - Market power of competitive fuels
- Carbon Dioxide – gram/km
- GHG impact of CH_4 due to system leakage (CH_4 = 21x CO_2)
- Other Pollutants (Particulate and NOx) – gram/km

Infrastructure for CNG

- Pipeline from well-head to major distribution point (large size/moderate pressure)
- Branching distribution lines to major user sites (small size/low pressure)
  - Modest storage buffer in system
- Compression onto vehicles (very high pressure)
  - This step can require substantial amounts of capital equipment
  - Modest Vehicle Range
- Explosion Proof Maintenance Facilities
  - Buses can be stored outside but are seldom repaired outside

Total infrastructure cost for distribution to customer sites is significant

Cost of fueling stations highly dependent on required fueling time and throughput

Infrastructure for LNG

- Centralized liquefaction facility (near well-head)
  - Combined Cycle Plant, Cogeneration Facility
- Distribution to customer sites via ship or truck
- Direct LNG fueling to vehicle or gasify/compress onto vehicle
  - Better storage buffer, better fuel quality control, more risk
- Explosion Proof Maintenance Facilities

Total infrastructure cost for distribution to customer sites & fueling can be less than with CNG

Operating cost for distribution to non-coastal locations can be much higher than for CNG

CNG/LNG as Vehicle Fuel

Natural Gas Engine Technology (Two Options)

- Lean Burn with DOC vs. Stoichiometric with a 3-way catalyst
  - Diesel pilot ignition or Spark Ignited Lean-Burn
  - Stoichiometric and Lean burn utilize O_2 Sensor feedback to control air/fuel ratio
    - Both sensitive to O_2 Sensor failure
  - DOCs need to be CH_4 optimized
- Closed vs. Open Loop System

Open loop is not an acceptable option

NG Spark Ignited Lean-Burn

- CNG or LNG Advantages
  - Lean Burn operation lowers NOx emissions
  - Closed Loop O_2 feedback control adjusts for fuel quality
  - Diesel engine derivative non-throttled efficiency, ~26%
  - Particulate emissions are inherently low, some fine PM
- CNG Fuel Concerns
  - Lean limit of ignition can result in excess methane emissions
  - Knock limits of blended gas can complicate engine operation

Natural Gas is lighter than air, explosion hazard

NG Diesel Ignited Lean-Burn

- Diesel Pilot Ignition Advantages
  - Electronically controlled diesel injection used to ignite natural gas
  - Lean misfire essentially eliminated, leaner operation possible, Lower NOx levels possible
  - Oxidation Catalyst still recommended
  - Lean Burn operation and O_2 feedback maintained
- Dual-Fuel Retrofits are not the same thing!
  - Conversion of a diesel engine to dual-fuel after the fact seldom work
  - Open loop non-feedback not recommended
  - Dual-fuel retrofits typically result in high NOx emissions similar to diesel alone
  - Exhaust moisture fluctuations can result in significant PM spikes

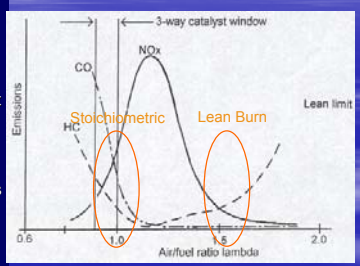
CNG Stoichiometric

- CNG Stoichiometric Combustion
  - Spark ignited configuration derived of a gasoline engine
  - Typical of light-duty CNG deployments
  - O_2 feedback with a three-way catalyst, very low emissions
    - CO, HC oxidation, NOx reduction
  - More tolerant of adverse fuel quality, altitude, etc.
  - Lower compression, less knock concerns
- Stoichiometric Concerns
  - Throttled, lower compression engine results in lower fuel economy, similar to gasoline efficiency
  - Power to weight can be managed but impacts hill climbing

Once again, open loop retrofits are not recommended

Emissions as a Function of Combustion Excess Air

- Emission levels as a function of combustion excess air
- Near excess air factor of 1:1 NOx emissions high, but 3-way catalyst can be used to reduce them (stoichiometric operation)
- NOx emission tail off as lean operation nears 1.6:1 excess air factor (lean-burn operation)



NG Engine Comparison Summary

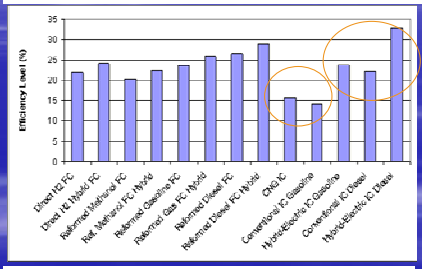
- What is the Gold Standard?
  - Diesel still sets the standard for economy, diesel hybrid more so
- CNG Stoichiometric Combustion (EU)
  - Lowest emissions of criteria pollutants (if 3-way catalyst is used)
  - Better Fuel Tolerance, Lower Torque
  - Less efficient throttled engine can be partially overcome with lower power/weight ratios
- CNG Lean-Burn (US)
  - More efficient option, higher engine torque
  - Higher overall criteria emissions than stoichiometric
  - Low fuel quality tolerance, methane emissions can increase GHG emissions

Fuel alone cannot guarantee low emissions, every NG vehicle to date has demonstrated ability for high emissions when components fail

Real World Experience shows that retrofits (especially dual-fuel) almost never produce expected emissions reductions

CNG/LNG as Onboard Fuel Efficiency

Figure 10: Comparison of Energy Efficiencies Between Fuel Cells, Internal Combustion and Hybrid Vehicles



Sources: Stodolsky et al., 1999; Albert Sorkey and Associates, 1996; Pembina Institute for Appropriate Development, 2000; and Thomas et al., 1998.

NG Fuel Quality

- Natural Gas Composition
  - In ground 70-90% methane
  - Delivered pipeline gas 85-99% methane
  - Pipeline quality standards based on electric generation
  - Can include relatively high levels of propane, butane (seasonal)
- NG internal combustion engines require tighter control of NG composition than other uses
  - Composition effects air/fuel ratio
  - Composition effects "octane" rating
- Inappropriate gas quality/composition leads to engine problems
  - Increased emissions & lower efficiency
  - Drivability problems and engine damage

Options for CNG & Electricity

- New Electricity Generation at Well-head
  - Little NG distribution infrastructure required
  - Some New electricity distribution infrastructure required
  - Potential for cogeneration of LNG using waste heat
- Conversion/Expansion of Existing Generation Sites
  - NG infrastructure required to generating sites
  - Little new electricity distribution infrastructure required
  - Potential for vehicle fueling with CNG near current sites

Depending on Current Method of Electricity Generation, either option may provide one of the "best" uses of new NG resources

Trolley Bus Case Study

- Rubber-tire electric trolley buses
- Zero emissions at point of service
- Ability to use regenerative braking
  - Recapture kinetic energy
  - Put back into transmission lines
- High Local Infrastructure & Operating Cost Compared to Diesel/CNG vehicles
- Essentially used for public transportation only
  - Dedicated bus way with overhead wire
  - Hybrid capability allows for off-wire travel to bus way from depot

May provide "best" use of NG to power public vehicles depending on total cost trade-offs

NG Conversion to Hydrogen

- Reform CNG off-board at centralized location
  - Transport hydrogen via pipeline
  - CNG infrastructure compatible with hydrogen increases costs
- Reform CNG off-board at de-centralized locations
  - Complicated fueling stations with high capital costs but can utilize existing CNG infrastructure
- Reform CNG on-board, lowest efficiency
  - Steam Reforming ~70 – 80 % efficient
  - Partial Oxidation ~ 50 % efficient

Hydrogen path was and is still 20 years out

NG Conversion to Synthetic Diesel Fuel

- Advantages
  - Produces very low sulfur diesel fuel
  - Results in almost negligible Particulate Matter emissions using DPF
  - Uses existing diesel fuel infrastructure (somewhat)
  - Leapfrog to EURO III/IV performance
- Disadvantages
  - Potential for contamination with higher sulfur diesel fuel
  - High capital investment for production facility

Closing Discussion

- There is more than one option for utilization of new NG resources for “clean” transportation
- Harmonize and optimize for all factors
  - Minimize criteria pollutant emissions
    - Leap forward to the newest US or EURO standards
  - Maximize fuel economy
    - Be aware of hybrid-electric and diesel competition
  - Minimize GHG emissions
    - Direct NG combustion may not be the most efficient option
  - Maximize capital recovery
    - NG may simply be more valuable in another application

Closing Discussion

To maximize emissions benefits from NG vehicles

- Focus on conversion of diesel vehicles
  - Potential benefits much higher than conversion from gasoline
- Use state of the art engine technology
  - Fuel alone does not guarantee low emissions
- Avoid Dual Fuel Retrofits
  - In-use emissions other than PM can actually increase
- Pay attention to methane emissions from engine and from distribution infrastructure
  - Offset CO_2 reductions for smaller net GHG benefit