The Potential Role for Shale Gas in Sustainable Light-Duty Transportation

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Argonne National Laboratory

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Presentation Overview

- Introduction to Argonne National Laboratory
- Overview of current trends in energy demand for transportation
- Investigation into the use of CNG in light duty transportation
  - Energy and Emissions testing of a CNG conversion vehicle
  - Evaluation of BiFuel CNG-Gasoline vehicles
    - Strategy
    - Study assumptions
    - Possibilities of bi-fuel conversions
    - Cost overview
    - Analysis of payback
- Summary and implications for future research
Argonne is One of DOE’s Largest Research Facilities

- The first national laboratory, chartered in 1946
- Operated by the University of Chicago for the U.S. Department of Energy
- Major research missions include basic science, environmental management, and advanced energy technologies
- About 2,900 employees, including about 1,000 scientists and engineers, of whom 750 hold doctorate degrees
- Annual operating budget of about $750 million (~80% from DOE)
- Since 1990, Argonne has worked with more than 600 companies and numerous federal agencies

Argonne National Laboratory occupies 1,500 wooded acres in DuPage County, Ill, about 25 miles southwest of Chicago.
Argonne Transportation Capabilities Support System Analysis

Transportation Hutch

APS – x-rays

Materials Research

- Battery electrodes
- Fuel cell catalysts
- Tribology

Basic and Applied Combustion Research

Advanced Powertrain Research Facility

Fuel Cell and Battery Testing

Testing and Validation

End of Life Vehicle Recycling

Autonomie GREET

Modeling and Simulation

High Performance Computing
Advanced Powertrain Research Facility

Benchmark

“Be the eyes and ears of automotive technology development for the Department of Energy”

Dynamometer Testing Research

- Vehicle level
  - Energy consumption (fuel + electricity)
  - Emissions
  - Performance
  - Vehicle operation and strategy
- ‘In-situ’ component and system testing
  - Component performance, efficiency and operation over drive cycles
  - Component mapping

Codes and Standards

Assist in codes and standards development with public and independent data
Goal: Energy Security

- Improve U.S. energy independence by displacing imported petroleum
  - Extraction of NG in the U.S. is expected to continually increase over the next 23 years

Price Comparison of Transportation Fuels

Recent Trends: Volatile Gas and Diesel prices → Stable CNG

U.S. Average Retail Fuel Prices

- Gasoline
- Diesel
- CNG
- Electricity*

*Electricity prices are reduced by a factor of 3.4 because electric motors are approximately 3.4 times as efficient as internal combustion engines

www.afdc.energy.gov/data/
Carbon Intensity of Possible Fuels

Carbon Intensity of Various Fuels in California LDVs

- California Reformulated Gasoline: 95.9
- Corn Ethanol: 95.7
- Sugarcane Ethanol: 73.4
- CNG: 67.7
- Hydrogen (from Nat. Gas): 61.8
- Electric (Calif. Mix): 41.4
- Ethanol (Forest Waste): 21.4
- Landfill CNG: 11.3

Data From: www.afdc.energy.gov/afdc/data/
Who Consumes Transportation Petroleum?

Primary segments of interest:

- Light Trucks: 30%
- Cars & Motorcycles: 28%
- Other Trucks: 19%
- Aircraft: 9%
- Boats & Ships: 5%
- Trains & Buses: 3%
- Military (All Uses): 3%
- Pipeline Fuel: 2%
- Lubricants: 1%

Source: U.S. Energy Information Administration, Annual Energy Outlook 2010, Reference Case, Table 45
Progress Made in Medium/Heavy-Duty Vehicles
CNG and Light Duty Transportation
Testing Objective

- Perform vehicle testing to obtain comparative vehicle-based fuel usage and emissions data on similar medium-duty truck applications

- Vehicle supplier’s cooperation was a key aspect of the testing, since they loaned Argonne two identically equipped Ford E-250 cable repair vans one of which was converted to CNG while the other was base case gasoline

- The purpose of the study was to evaluate the current state of CNG technology for the Clean Cities Program
MPG(e) Comparison

Miles per gallon of gasoline equivalent [MPG(e)] is the common fuel economy metric adopted by EPA to allow the comparison of alternative fuel and advanced technology vehicles with conventional internal combustion powered vehicles. The amount of CNG consumed is converted into gallons of gasoline equivalent on the basis of the lower heating content of CNG compared to gasoline\(^1\).

<table>
<thead>
<tr>
<th></th>
<th>Petrol MPG</th>
<th>CNG MPG(e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FTP#1</td>
<td>11.66</td>
<td>10.05</td>
</tr>
<tr>
<td>FTP#2</td>
<td>11.63</td>
<td>10.06</td>
</tr>
<tr>
<td>HWY#1</td>
<td>18.69</td>
<td>16.73</td>
</tr>
<tr>
<td>HWY#2</td>
<td>18.64</td>
<td>16.60</td>
</tr>
</tbody>
</table>

\(^1\) The equation used is: \[\text{MPG(e)} = \frac{\text{CWF}_{\text{NG}} \times D_{\text{NG}} \times 21.5}{(0.749 \times \text{CO}_1) + (\text{CWF}_{\text{NO}} \times \text{NO}) + (0.429 \times \text{CO}) + (0.273 \times (\text{CO}_1 - \text{CO}_{\text{NO}}))}\] where \(\text{CO}_1\), \(\text{NO}\), \(\text{O}_{\text{NO}}\), \(\text{CWF}_{\text{NO}}\), \(\text{CWF}_{\text{NG}}\), \(\text{CO}_2\), and \(\text{NO}_{\text{NO}}\).
However, CNG has Lower CO2 Emissions

CNG is a low-carbon fuel, as such the CO2 emissions are lower despite higher fuel consumption. (CNG carbon weight fraction is 0.715, gasoline is 0.863)
Methane Emitted is Higher in CNG

Gasoline vehicles typically emit low percentages of methane. For CNG, methane is the major hydrocarbon constituent emitted.
However, Methane Levels are Not High in the Context of Greenhouse Gas Potential

Adding methane with 21x CO2

Note only small increase in GHG potential
Summary of Findings

- **Test Consistency**: The test-to-test consistency of the Fuel Economy (FE) measurements was excellent and surpassed typical error bars for comparisons between two different vehicles.

- **Fuel Consumption**: The CNG van consumed 1.6 to 2.0 MPG(e) more fuel than the gasoline van over the same test cycles. Some of the fuel consumption increase can be explained by the increased curb weight (+750 lbs.) due to the addition of the CNG fuel system and steel pressure tanks.

- **CO2 Emissions**: The CNG van produced 20% lower CO2 emissions.

- **Methane Emissions**: The CNG van produced a relatively small increase in measured methane emissions (3.5 to 12 times higher) attributed to expected small amounts of fugitive emissions.

- **Green House Gas Potential** calculated is about 18% less from the CNG van versus the gasoline counterpart due to the combination of reduced CO2 coupled with a minor increase of methane emissions.

- **CO and NOx Emissions**: The CNG van produced 40% lower g/mi CO and 40% higher g/mi NOx compared to the gasoline version over the FTP urban cycle. The additional weight of the CNG conversion vehicle contributes to the NOx increase observed versus baseline gasoline vehicle.
Vehicle Feature Comparison: Honda Civic-CNG vs Honda Civic-Gasoline

- Civic Natural Gas differs from Civic Gasoline in several important ways
  - Specific Power Output reduced
  - Engine CR Increased 2.1 points
    - Partially via piston crown change

Note: Transmission ratios are identical

<table>
<thead>
<tr>
<th>Feature</th>
<th>MY 2012 Honda Civic Natural Gas</th>
<th>MY 2012 Honda Civic Gasoline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle Architecture</td>
<td>Alternative Fuel</td>
<td>Conventional Vehicle</td>
</tr>
<tr>
<td>Test Weight</td>
<td>3,125 lbs</td>
<td>3,125 lbs</td>
</tr>
<tr>
<td>Powertrain</td>
<td>Engine 1.8L SOHC I-4 w/ i-VTEC VVT (110 hp@ 6500 rpm, 106 lbf-ft @ 4300 rpm) CR: 12.7:1</td>
<td>Engine 1.8L SOHC I-4 w/ i-VTEC VVT (140 hp@ 6500 rpm, 128 lbf-ft @ 4300 rpm) CR: 10.6:1</td>
</tr>
<tr>
<td></td>
<td>Transmission 5-Speed Torque Converter Automatic</td>
<td>Transmission 5-Speed Torque Converter Automatic</td>
</tr>
<tr>
<td>Fuel Storage</td>
<td>Fuel Storage Composite w/ Aluminum Liner 8.0 Gasoline Gallon Equivalent @ 3600 psi</td>
<td>Fuel Storage Conventional Fuel Tank, 13.2 gal</td>
</tr>
<tr>
<td>EPA Label Fuel Economy</td>
<td>27 City / 38 Hwy / 31 Combined mpge</td>
<td>28 City / 39 Hwy / 32 Combined mpg</td>
</tr>
<tr>
<td>Performance</td>
<td>Reported 0-60 Time: 10.5s</td>
<td>Reported 0-60 Time: 9.0s</td>
</tr>
</tbody>
</table>
Strategy For Rapid Deployment:
A Path from Bi-Fuel to Dedicated

- Is rapid deployment possible without new inventions?

1) Immediate deployment using current technology

2) Home and public refueling
   - Optimized engine eff.
   - Cheaper tanks
   - Cheaper compressor

3) Dedicated, public fueling
   - Cheap, light tanks
   - Optimized engine technologies
Compressor Performance

- Home refueling stations can be a significant investment (~$4,000-$7,000)
- Importance of leveraging performance and cost
  - Fueling rate required to completely refuel the vehicle overnight
  - Service pressure
  - Efficient use of electricity
- Electricity consumption can add a significant cost

### Compressor Operating Cost

- Assumptions:
  - 3600 psi
  - Pure methane
  - $0.12/kWh

### BRC Fuel Maker

<table>
<thead>
<tr>
<th>Model</th>
<th>FMQ 2-36 @60Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow Rate</td>
<td>1 gal/hr</td>
</tr>
<tr>
<td>Power</td>
<td>1.9 kW</td>
</tr>
</tbody>
</table>

1.9 kWh/gal eq.
~43% Efficiency
Bi-Fuel Worth Attention? A Comparison

AT HOME “RANGE-EXTENDED” ALT FUEL VEHICLES

EREV PHEV

- Alternative fuel for **25-50 miles**
- Domestic and clean alternative fuel
- High battery costs (~$10k-15k)
- Storage weight: 435 lbs
- Charger and EVSE costs (~$1.5k)
- High cost hybrid drive with critical materials in motors

“Plug-in HEV”

Bi Fuel CNG

- Alternative fuel for **75-100 miles**
- Domestic and clean alternative fuel
- Low CNG tank costs (~$300)
- Storage weight: 100 lbs
- Compressor costs ($4-7k) [$500 possible?]
- Modest fuel system costs ($1-2k)

“Pipe-in NGV”
Bi-Fuel CNG Study

- Using PHEV analysis methods, analyze feasibility and cost motivators
- Utility Factors useful in estimating CNG use
- Develop models that highlight responses to fundamental input assumptions
  - Are there optimum designs?
  - Where are diminishing returns?
  - What targets can be made for greatest cost savings?
  - What input factors are key for successful designs?
Selection of Baseline Vehicle

2011 Sales

<table>
<thead>
<tr>
<th>Rank</th>
<th>Model</th>
<th>Sales</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ford F-Series</td>
<td>584,917</td>
</tr>
<tr>
<td>2</td>
<td>Chevy Silverado</td>
<td>415,130</td>
</tr>
<tr>
<td>3</td>
<td>Toyota Camry</td>
<td>308,510</td>
</tr>
<tr>
<td>4</td>
<td>Nissan Altima</td>
<td>268,981</td>
</tr>
<tr>
<td>5</td>
<td>Ford Escape</td>
<td>254,293</td>
</tr>
<tr>
<td>6</td>
<td>Ford Fusion</td>
<td>248,067</td>
</tr>
<tr>
<td>7</td>
<td>Ram Pickups</td>
<td>244,763</td>
</tr>
<tr>
<td>8</td>
<td>Toyota Corolla/Matrix</td>
<td>240,259</td>
</tr>
<tr>
<td>9</td>
<td>Honda Accord</td>
<td>235,625</td>
</tr>
<tr>
<td>10</td>
<td>Chevy Cruze</td>
<td>231,732</td>
</tr>
</tbody>
</table>

7 of top 10 models represented in these two platforms (76% sales)
Comprehensive Analysis Spreadsheet Developed to Generate Results

### Relative Petroleum Displacement

![Relative Petroleum Displacement Graph]

### Possible CNG Tank Dimensions

![Possible CNG Tank Dimensions Graph]

### First Year Individual Cost Savings

![First Year Individual Cost Savings Graph]

### Cost of Vehicle Ownership

![Cost of Vehicle Ownership Graph]

### Sensitivity Curve for CNG Tank Capacity

![Sensitivity Curve for CNG Tank Capacity Graph]

### Sensitivity to HRA Purchase Price

![Sensitivity to HRA Purchase Price Graph]

### Bi-Fuel Vehicle Savings: Midsize Car

![Bi-Fuel Vehicle Savings: Midsize Car Graph]

### Bi-Fuel Vehicle Savings: Pickup Truck

![Bi-Fuel Vehicle Savings: Pickup Truck Graph]
Example Factor: Estimated MPGe for CNG

- Survey completed for several bi-fuel vehicles
- Examples below: (4% to 8% lower MPG)
- Conclusion: Assume 5% fuel economy penalty for bi-fuel vehicle throughout calculations

<table>
<thead>
<tr>
<th>MY 2003 Vehicles</th>
<th>Chevy Cavalier</th>
<th>Ford F-150 2WD</th>
<th>Ford F-150 4WD</th>
<th>GM 2500 2WD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gasoline</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>City fuel econ.</td>
<td>mpg</td>
<td>21</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Hwy fuel econ.</td>
<td>mpg</td>
<td>30</td>
<td>15</td>
<td>14</td>
</tr>
<tr>
<td>Combined fuel econ.</td>
<td>mpg</td>
<td>25.1</td>
<td>12.8</td>
<td>12.4</td>
</tr>
<tr>
<td><strong>Natural Gas</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>City fuel econ.</td>
<td>mpg</td>
<td>20</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>Hwy fuel econ.</td>
<td>mpg</td>
<td>29</td>
<td>14</td>
<td>13</td>
</tr>
<tr>
<td>Combined fuel econ.</td>
<td>mpg</td>
<td>24.1</td>
<td>12.4</td>
<td>11.4</td>
</tr>
<tr>
<td><strong>Relative econ.</strong></td>
<td><strong>96%</strong></td>
<td><strong>96%</strong></td>
<td><strong>92%</strong></td>
<td><strong>95%</strong></td>
</tr>
</tbody>
</table>

www.fueleconomy.gov
Example Factor: Tank Size and Cost Calculation Tools

- The length, diameter, and number of storage tanks may be optimized
  - Primarily dependent on vehicle size and desired range
  - Assuming 3600 psi service pressure
- Cost model based upon tank steel and fabrication costs
  - Correlated with tank manufacture's price lists

Conclusion:
Determined Price = $129*GGE+42
Estimate CNG/Gasoline Use

- Utility Factor Analysis - *Impact*
  - “Fleet UF”: Determines annual miles driven on CNG versus gasoline
  - “Individual UF”: Probability-weighted fraction of individual’s CNG use

- Commuting Scenario – *Market Pull*
  - Value proposition for varying daily commuting requirements
  - Cost payback scenarios for specific individual
Savings - CNG/Gasoline Use Conclusions

- With only 4-5.5 GGE needed, cheap, Type 1 tanks are proposed
- Although high utility is found with small tanks, with only marginal increased costs, larger tanks offer increased fuel savings. A range of 100 miles was chosen.
  - 100 miles range → Car: 4 GGE, Truck: 5.5 GGE = 86%
- Overall fleet fuel savings is substantial
  - Midsize saves 442 gal/year
  - Pickup saves 605 gal/year
- Consumer fuel costs are substantially reduced for both the midsize sedan and the pickup, from ~$900 and ~$1,300 per year, respectively. This is roughly a 45% savings.

Are savings enough to justify extra costs?
### Initial Vehicle Costs - Baseline Assumptions

**Compressor (for 5.5 GGE Pick-Up)**

<table>
<thead>
<tr>
<th>Home Refueling Appliance Cost Model</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Filling Time</td>
<td>8 hours</td>
<td></td>
</tr>
<tr>
<td>Installation Price</td>
<td>$1,375.00</td>
<td></td>
</tr>
<tr>
<td>Maintenance</td>
<td>$0.20/gal eq.</td>
<td>$132.96</td>
</tr>
<tr>
<td>Ideal Compressor Flow Rate</td>
<td>0.29 GGE/hr</td>
<td></td>
</tr>
<tr>
<td>Compressor Price</td>
<td>$3,266.02</td>
<td>1</td>
</tr>
<tr>
<td>Annual Maintenance</td>
<td>$132.96</td>
<td></td>
</tr>
</tbody>
</table>

#### Vehicle Components

<table>
<thead>
<tr>
<th>Conversion Components</th>
<th>Cost</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder PRD &amp; ESV</td>
<td>$300.00</td>
<td>Type 1 small 3-5 GGE tanks</td>
</tr>
<tr>
<td>Brackets</td>
<td>$50.00</td>
<td>Integrated into the vehicle design</td>
</tr>
<tr>
<td>Manual Shutoff Valve</td>
<td>$50.00</td>
<td>High-volume</td>
</tr>
<tr>
<td>Receptacle</td>
<td>$70.00</td>
<td></td>
</tr>
<tr>
<td>SS Tubing</td>
<td>$50.00</td>
<td></td>
</tr>
<tr>
<td>Misc. Fittings &amp; Hardware</td>
<td>$50.00</td>
<td></td>
</tr>
<tr>
<td>Fuel Rails</td>
<td>$40.00</td>
<td></td>
</tr>
<tr>
<td>Regulator</td>
<td>$200.00</td>
<td></td>
</tr>
<tr>
<td>Fuel Filter</td>
<td>$80.00</td>
<td></td>
</tr>
<tr>
<td>Gauges</td>
<td>-</td>
<td>Built into IP</td>
</tr>
<tr>
<td>Fuel Lines</td>
<td>$20.00</td>
<td></td>
</tr>
<tr>
<td>Injectors</td>
<td>$200.00</td>
<td></td>
</tr>
<tr>
<td>Control Module</td>
<td>-</td>
<td>Same computer, more calibrations</td>
</tr>
<tr>
<td>Warranty</td>
<td>$111.00</td>
<td>10% of component cost</td>
</tr>
<tr>
<td>Total Cost</td>
<td>$1,221.00</td>
<td></td>
</tr>
<tr>
<td>Total Price</td>
<td>$1,526.25</td>
<td>25% markup</td>
</tr>
</tbody>
</table>

- If components priced today, costs are much higher
- Realistic supplier costs for 100,000 unit vehicle run
- Commonality of parts likely for cost reductions
Savings heavily dependent on mileage traveled per year.
Average Pick-Up Driver - Variable Home Refueling Appliance (HRA) Payback

- More favorable payback scenario due to higher fuel consumption
- Cost savings exist immediately at high mileage traveled even with high compressor costs.
Summary: Home Refueling Appliance Price Reduction Required

The full-size pickup segment has the highest consumer cost savings potential for a bi-fuel vehicle.

HRA costs must be reduced in order to achieve cost savings for:
- Lower average yearly mileage
- Higher fuel economy vehicles

<table>
<thead>
<tr>
<th>Segment</th>
<th>Average (13.5k mi/yr)</th>
<th>High Miles (20k mi/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full-Size Pickup</td>
<td>40%</td>
<td>None</td>
</tr>
<tr>
<td>Mid-Size Sedan</td>
<td>90% (unrealistic HRA price)</td>
<td>30%</td>
</tr>
</tbody>
</table>
Future Analysis and Implications

- Improvements in infrastructure and vehicle technology have the potential to greatly improve the cost effectiveness of CNG in light duty transportation.

- As improvements are made, input factors will need to be updated to reflect changes in:
  - CNG component pricing
  - HRA costs (unit, installation, and maintenance)
  - Variations in petroleum fuel costs
  - Improved CNG engine efficiencies
Questions?

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