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

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Argonne National Laboratory

10/2/2013

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

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

- 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

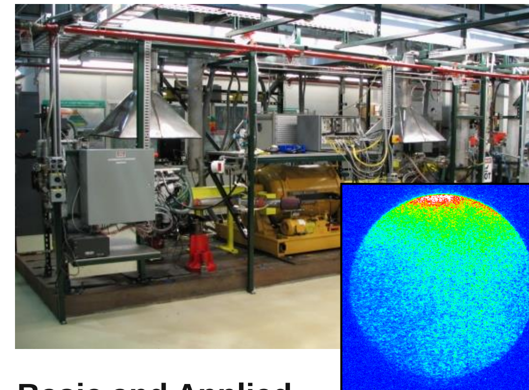
Argonne Transportation Capabilities Support System Analysis

Transportation Hutch

APS – x-rays

Materials Research

- Battery electrodes
- Fuel cell catalysts
- Tribology



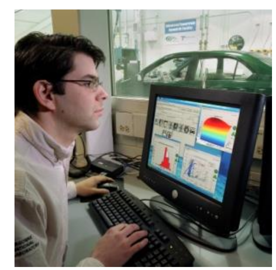
Basic and Applied Combustion Research

End of Life Vehicle Recycling

Advanced Powertrain Research Facility

Fuel Cell and Battery Testing

Testing and Validation



Autonomie

GREET

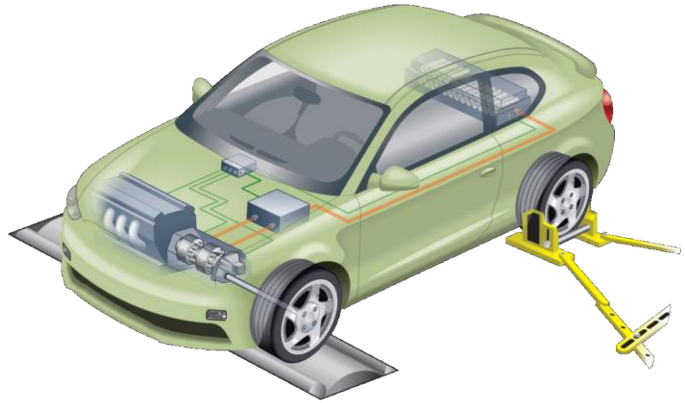
High Performance Computing

Modeling and Simulation

Advanced Powertrain Research Facility

Benchmark

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



U.S. DEPARTMENT OF ENERGY

Codes and Standards

Assist in codes and standards development with public and independent data

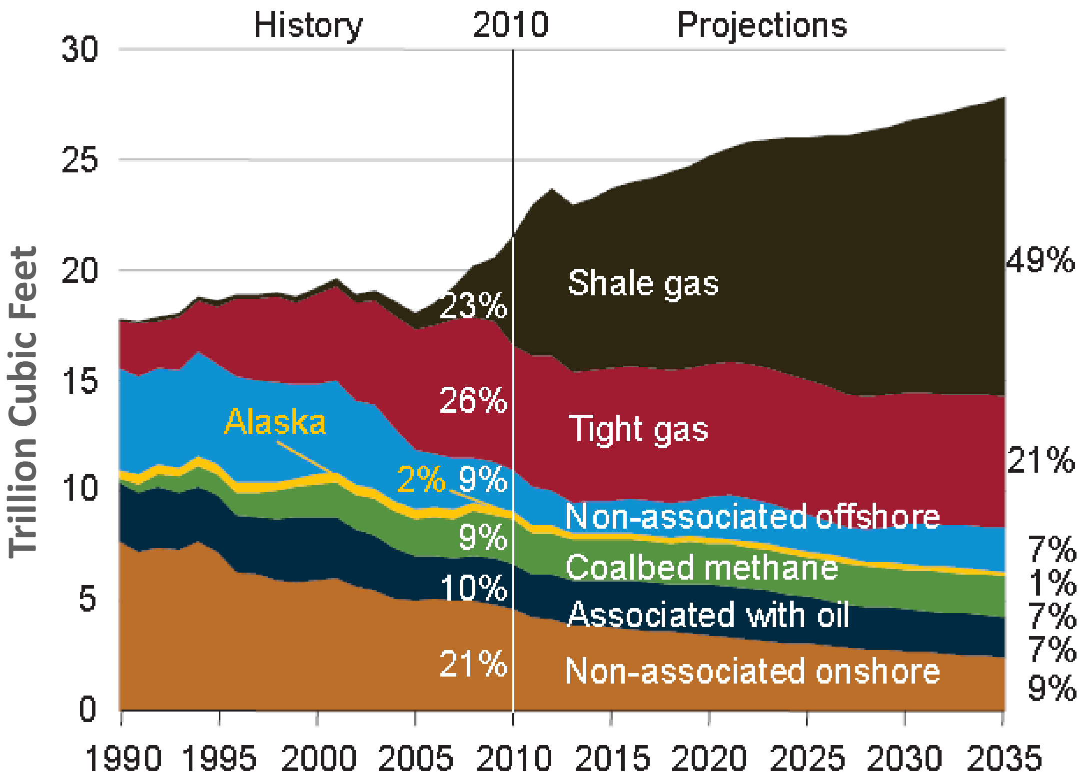
- **Dynamometer Testing Research**
  - Vehicle level
    - Energy consumption (fuel + electricity)
    - Emissions
    - Performance
    - Vehicle operation and strategy
  - 'In-situ' component and system testing
    - Component performance, efficiency and operation over drive cycles
    - Component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

4WD chassis dyno

2WD chassis dyno

Goal: Energy Security

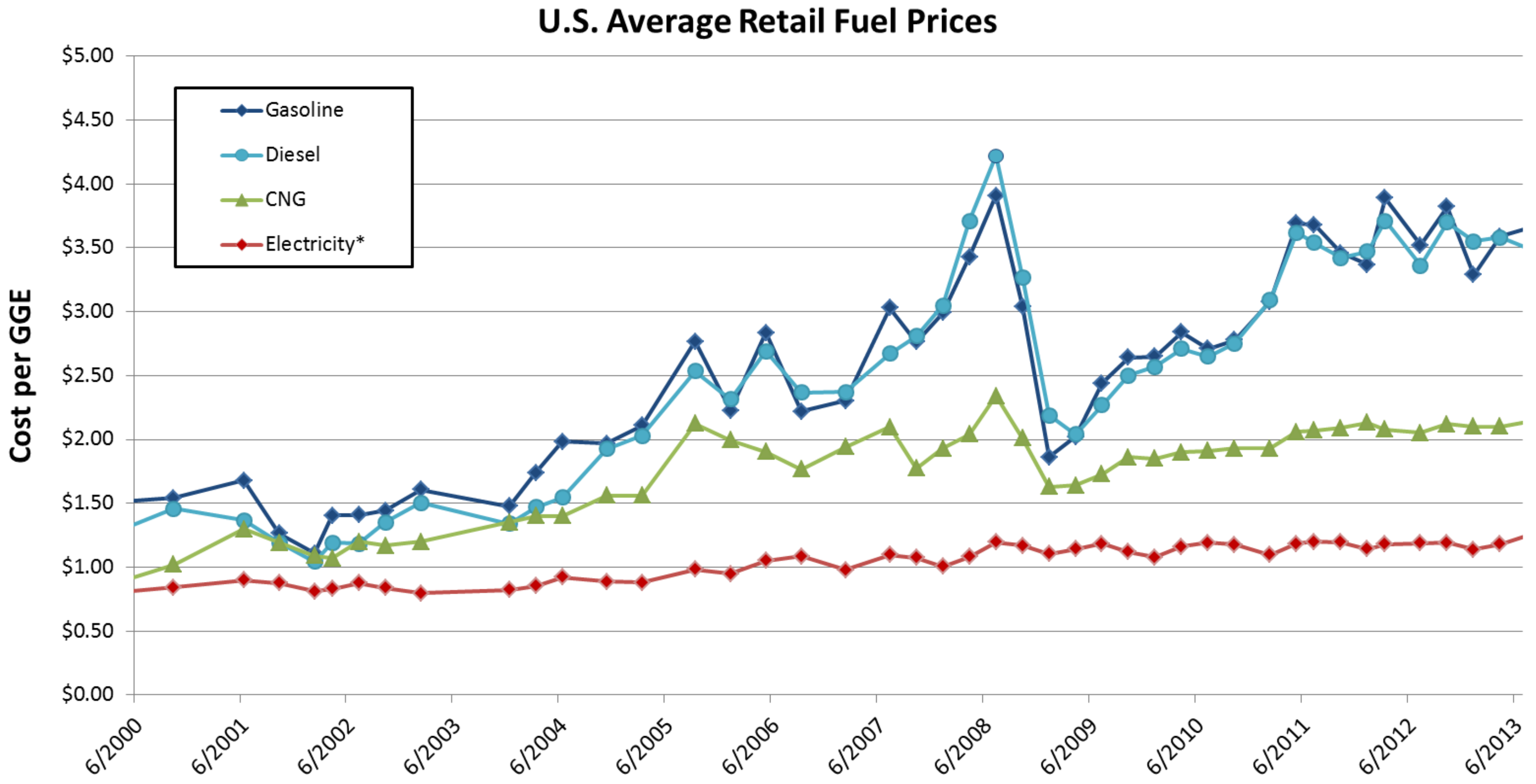
- Improve U.S. energy independence by displacing imported petroleum
  - Extraction of NG in the U.S. is expected to continually increase over the next 23 years[1]



1) U.S. Energy Information Administration. "AEO2012 Early Release Overview". Retrieved 4/5/12: http://www.eia.gov/forecasts/aeo/er/

Price Comparison of Transportation Fuels

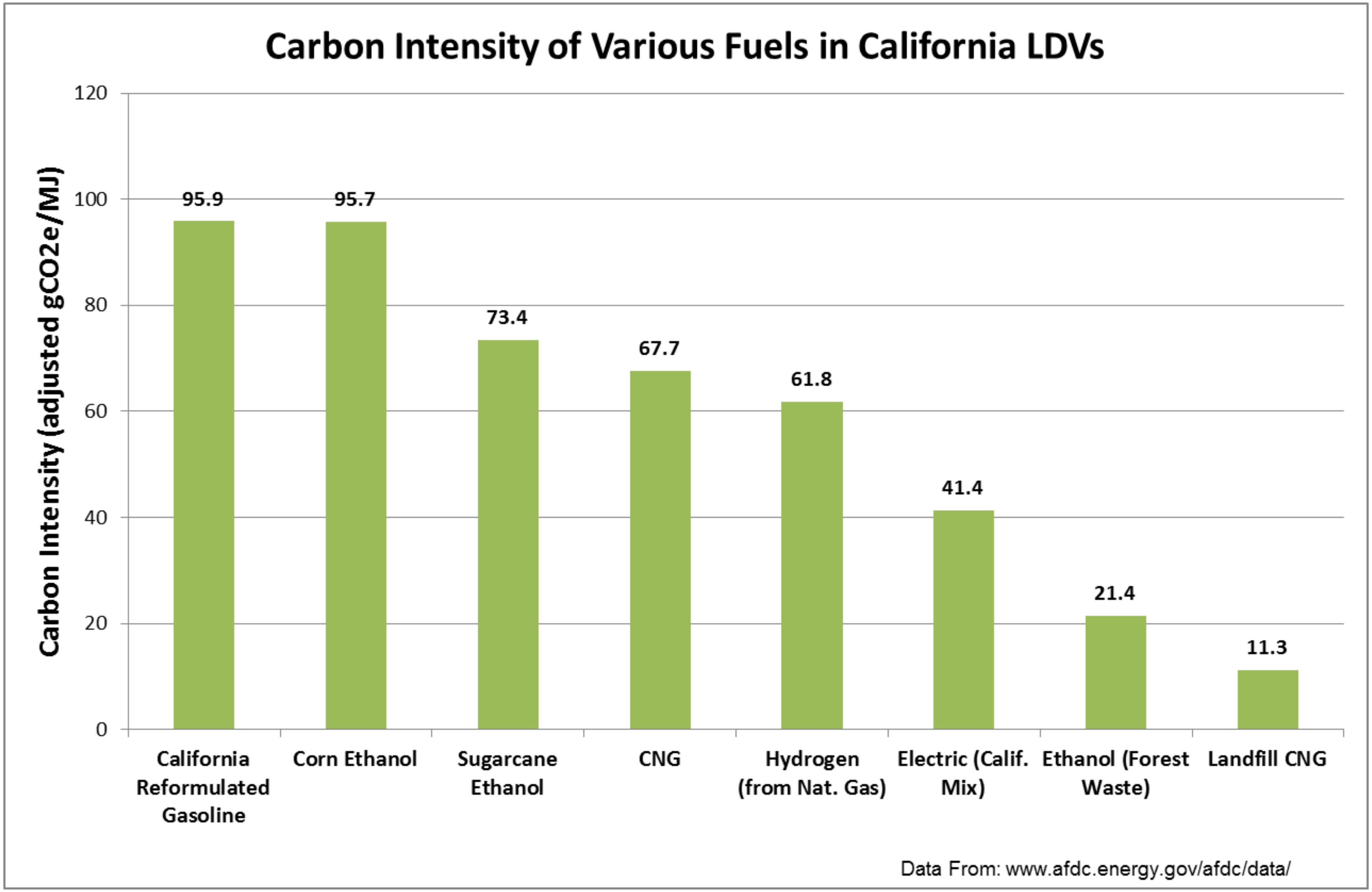
Recent Trends: Volatile Gas and Diesel prices→ Stable CNG



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

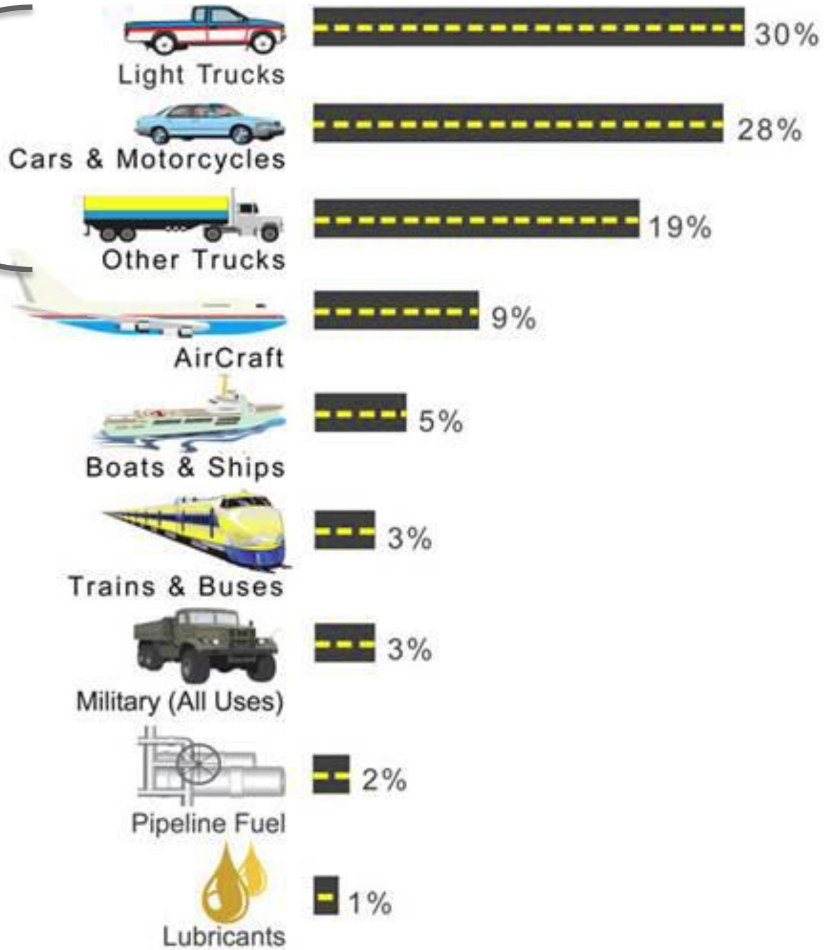
www.afdc.energy.gov/data/

Carbon Intensity of Possible Fuels



Who Consumes Transportation Petroleum?

Primary segments of interest



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2010, Reference Case*, Table 45

Progress Made in Medium/Heavy-Duty Vehicles

CNG

CNG and Light Duty Transportation

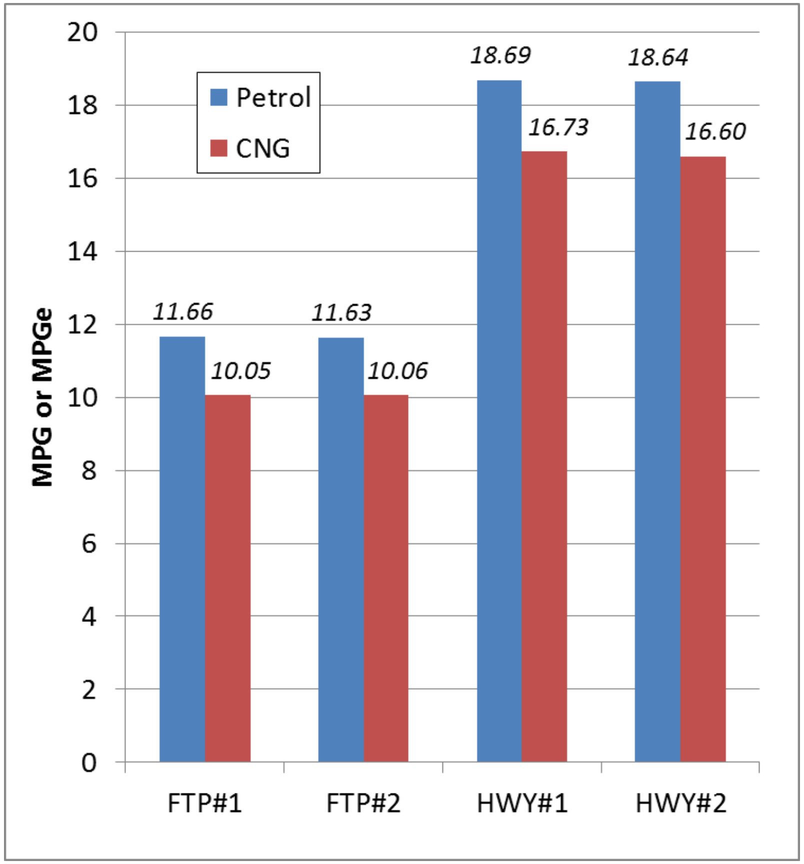
Testing Objective

- 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].

	Petrol MPG	CNG MPG(e)
FTP#1	11.66	10.05
FTP#2	11.63	10.06
HWY#1	18.69	16.73
HWY#2	18.64	16.60



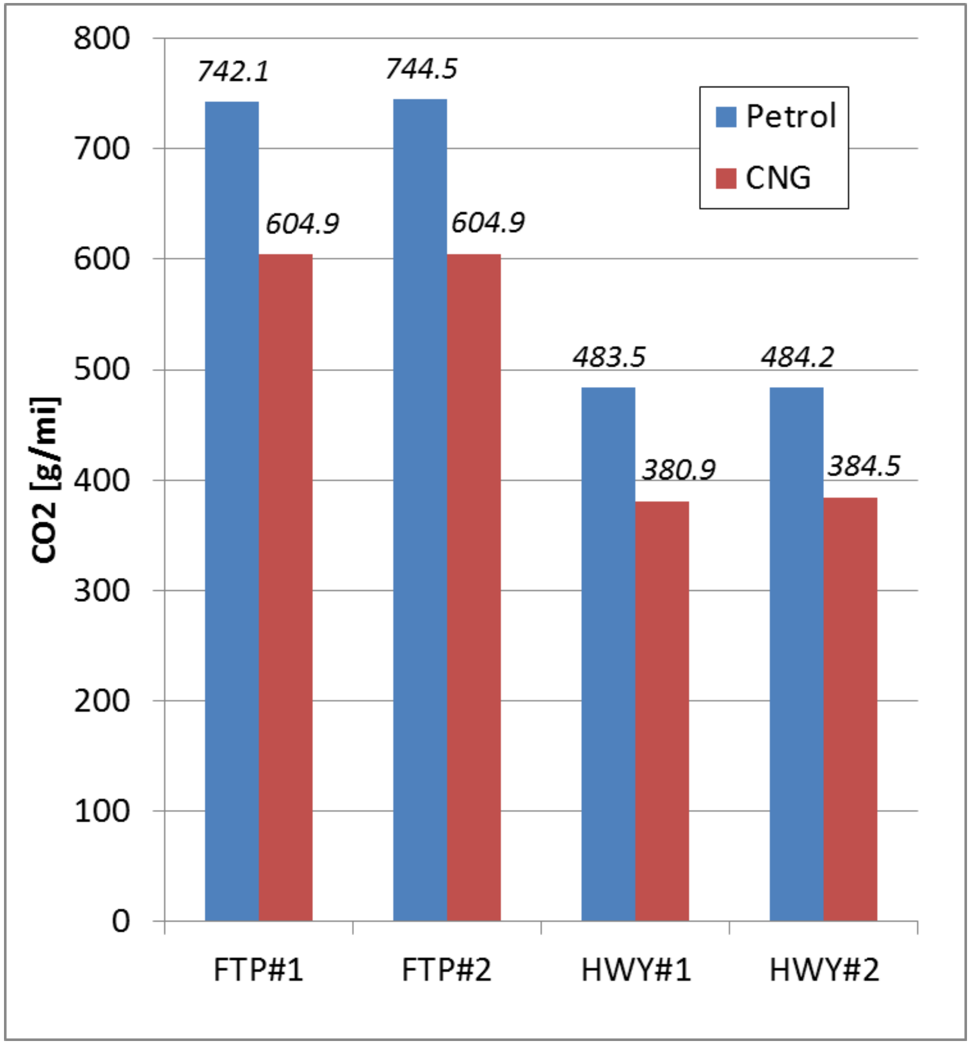
[1] The equation used is: $mpg_e = \frac{CWF_{HC/NG} \times D_{NG} \times 121.5}{(0.749 \times CH_4) + (CWF_{NMHC} \times NMHC) + (0.429 \times CO) + (0.273 \times (CO_2 - CO_{2NG}))}$ where $CO_{2NG} = FC_{NG} \cdot D_{NG.1} \cdot WF_{CO2}$ and $FC_{NG} = \frac{0.749 \cdot CH_4 + CWF_{NMHC} \cdot NMHC + 0.429 \cdot CO + 0.273 \cdot CO_2}{CWF_{NG} \cdot D_{NG.1}}$

$D_{NG.1} = SG_{fuel.AIR} \cdot 28.316847 \cdot 1.2047$

However, CNG has Lower CO2 Emissions

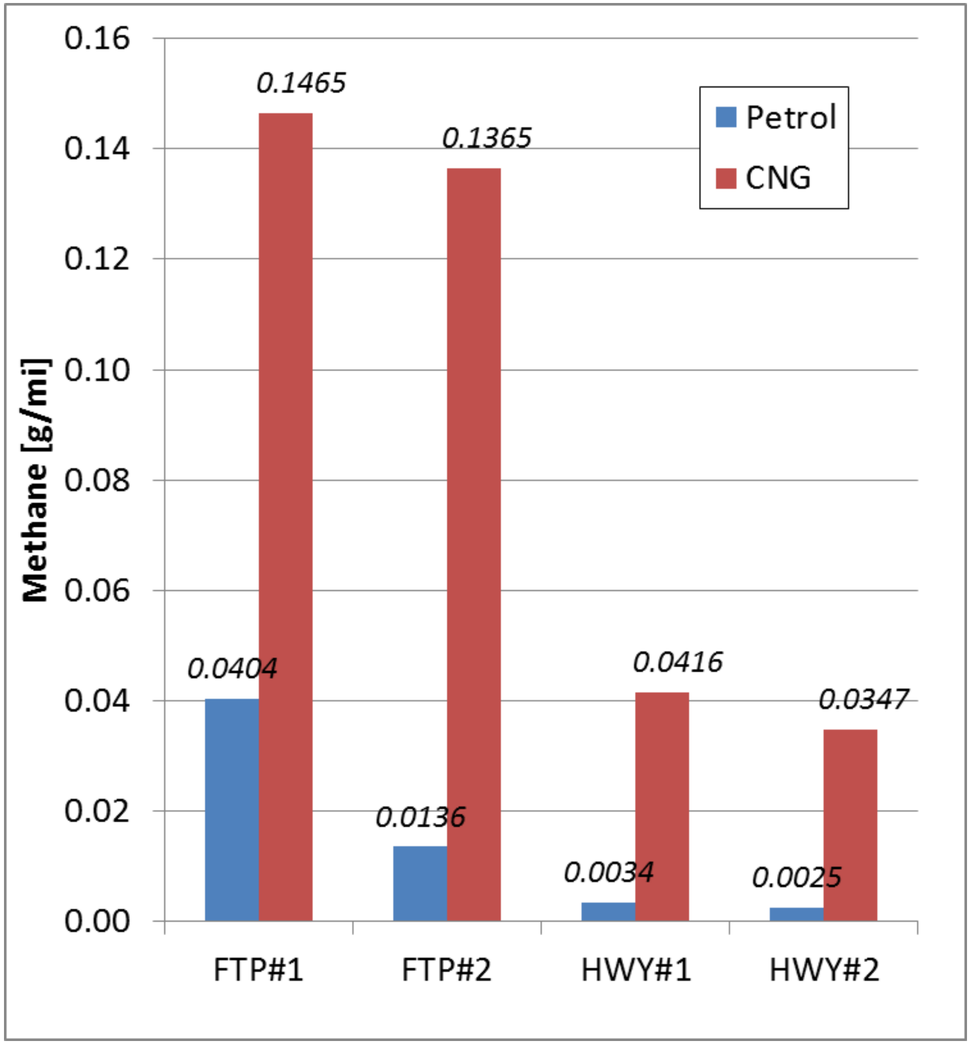
CNG is a low-carbon fuel, as such the CO2 emissions are lower despite higher fuel consumption

(CNG carbon weight fraction is 0.715, gasoline is 0.863)

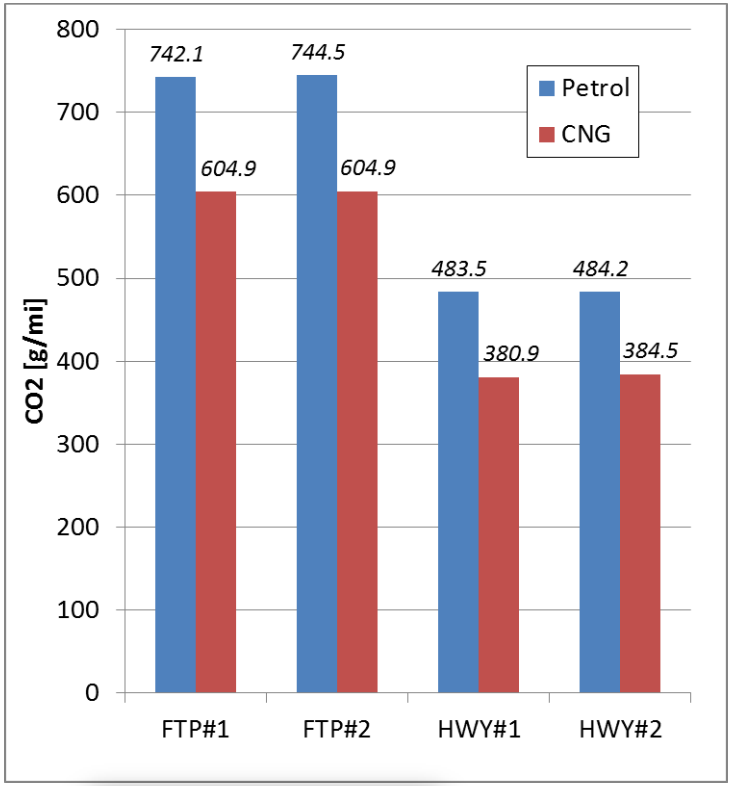


Methane Emitted is Higher in CNG

Gasoline vehicles typically emit low percentages of methane. For CNG, methane is the major hydrocarbon constituent emitted.

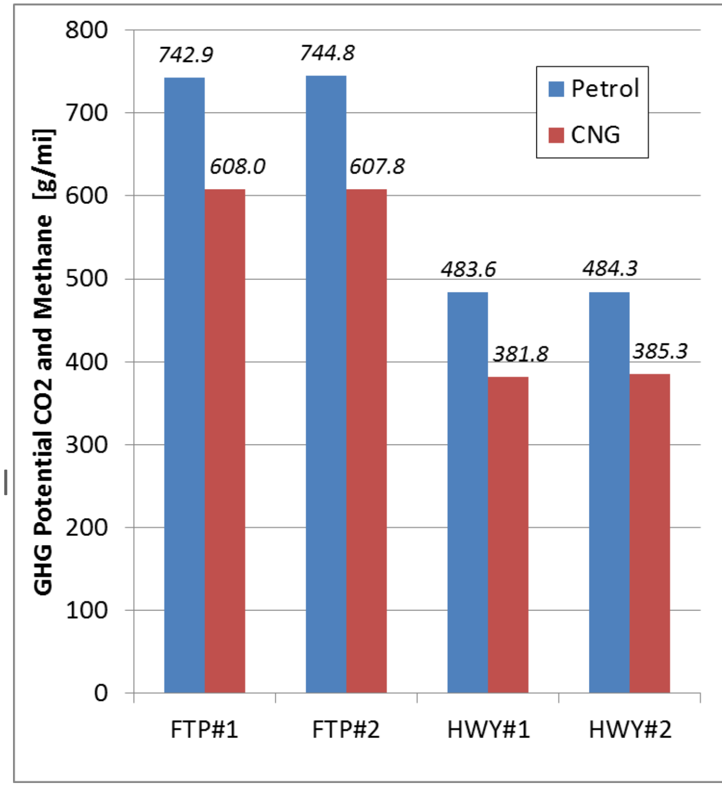


However, Methane Levels are Not High in the Context of Greenhouse Gas Potential



Adding methane with 21x CO2

Note only small increase in GHG potential



APTA Climate Change Standards Working Group
APTA CC-RP-001-09
8/14/09

Recommended Practice for Quantifying Greenhouse Gas Emissions from Transit

August, 2008
SUDS Climate Change Working Group

January, 2009
Technical Oversight Review

August, 2009
SUDS Policy and Planning Committee

TYPICAL SOURCES OF EMISSIONS
Figure 6

Gas	Typical Sources for Transit Agencies	GWP
Carbon dioxide (CO_2)	Gasoline and diesel combustion Combustion at stationary sources, e.g. maintenance yards Electricity purchases	1
Methane (CH_4)	Gasoline and diesel combustion Fugitive emissions of natural gas	21
Nitrous oxide (N_2O)	Gasoline and diesel combustion	310
Hydrofluorocarbons (HFCs)	Leakage of refrigerants	Varies[1]
Perfluorocarbons (PFCs)	Leakage of refrigerants	Varies[1]
Sulfur hexafluoride (SF_6)	Leakage from electrical equipment	23,900

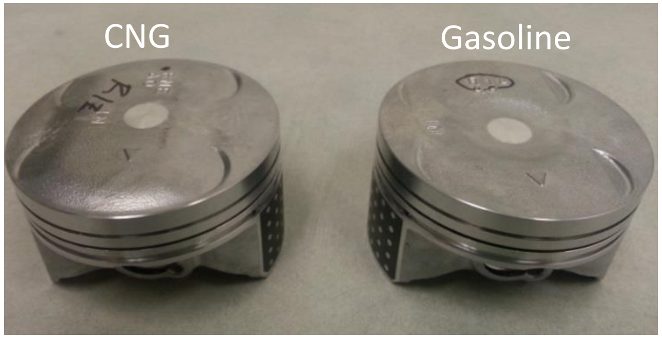
1. Varies by specific gas. See Appendix B of The Climate Registry General Reporting Protocol.

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

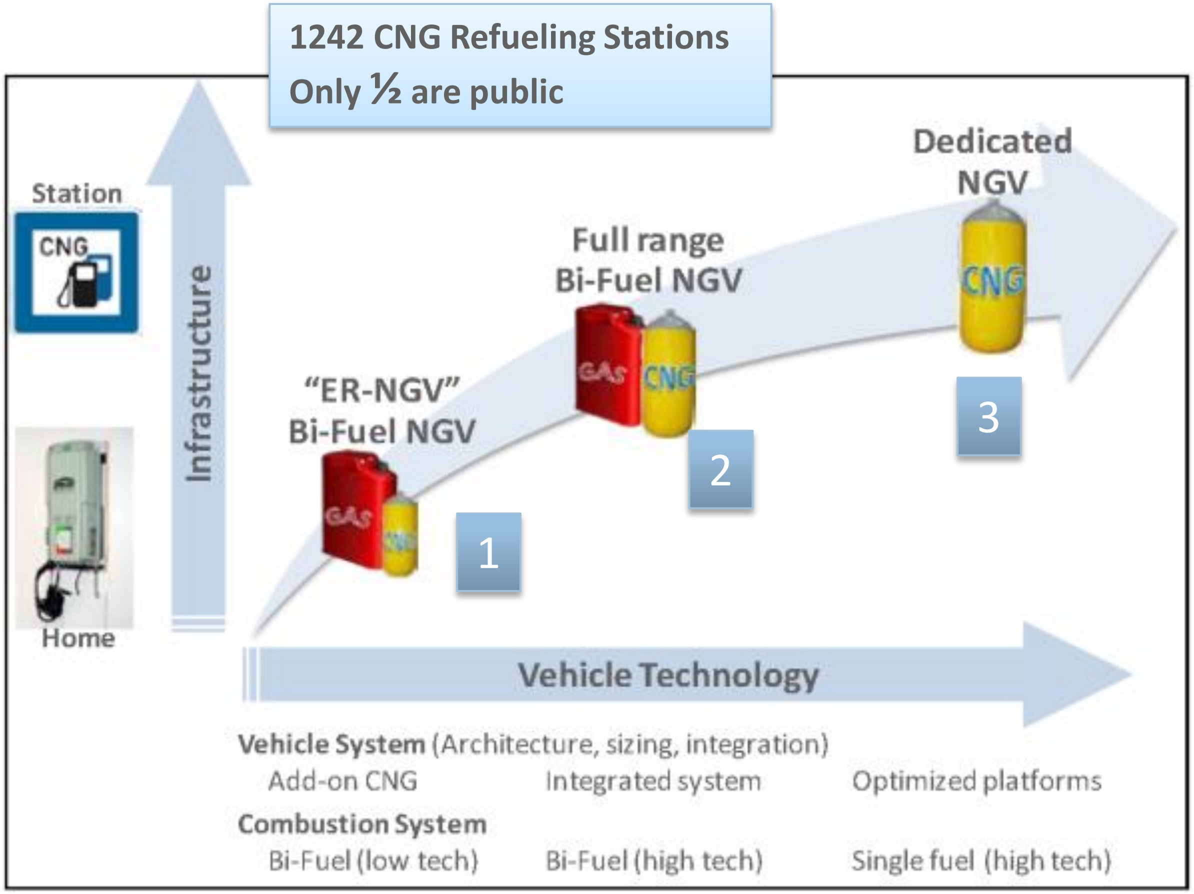


Note: Transmission ratios are identical

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

Strategy For Rapid Deployment: A Path from Bi-Fuel to Dedicated

- Is rapid deployment possible without new inventions?



1) Immediate deployment using current technology

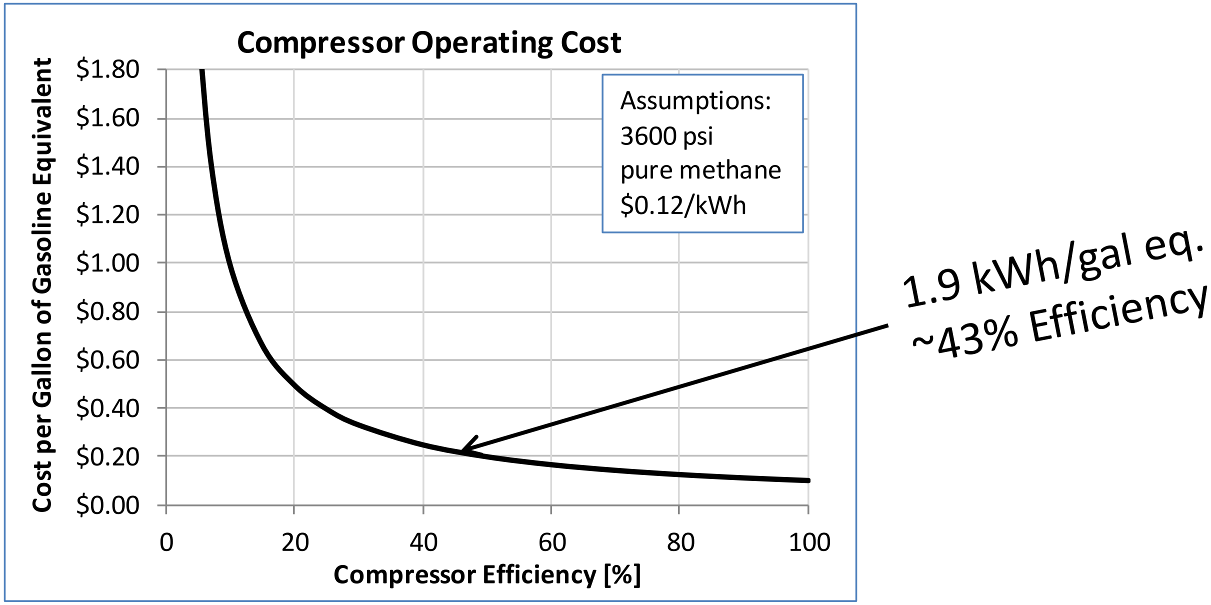
2) Home and public refueling
   - Optimized engine eff.
   - Cheaper tanks
   - Cheaper compressor

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

Model	FMQ 2-36 @60Hz
Flow Rate	1 gal/hr
Power	1.9 kW

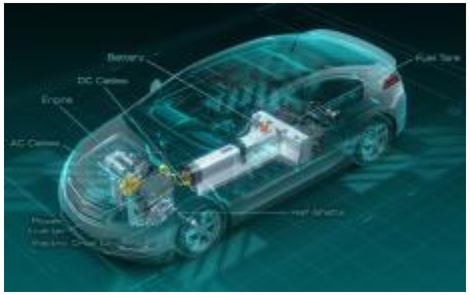


BRC Fuel Maker

Bi-Fuel Worth Attention? A Comparison

AT HOME "RANGE-EXTENDED" ALT FUEL VEHICLES

EREV PHEV



"Plug-in HEV"

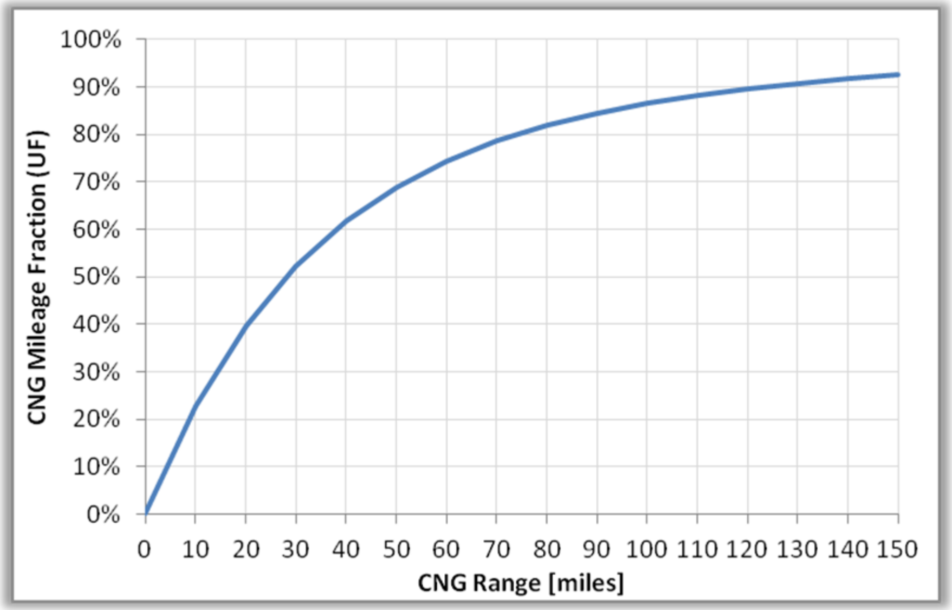
- Alternative fuel for **25-50 miles**
- Domestic and clean alternative fuel
- High battery costs (~$10k-15k)
- Storage weight: 435 lbs
- Charger and EVSE costs (~$1.5k)
- High cost hybrid drive with critical materials in motors

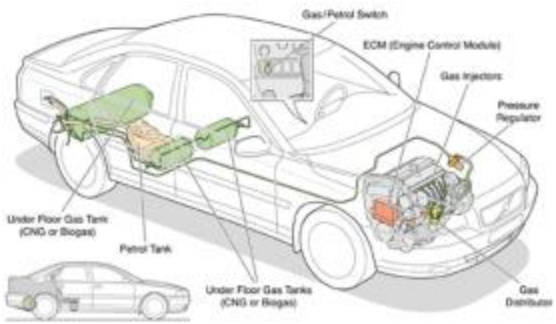
Bi Fuel CNG

"Pipe-in NGV"

- 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)

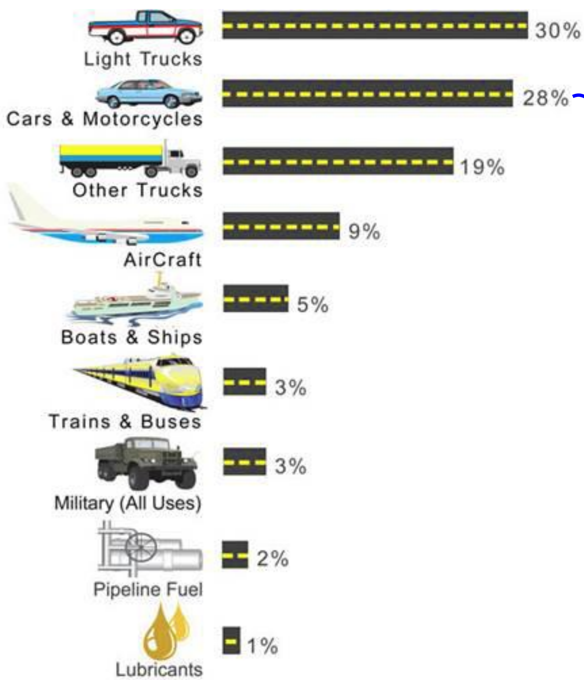
Bi-Fuel CNG Study





- 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



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2010, Reference Case*, Table 45

2011 Sales

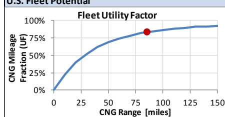
Rank	Model	Sales
1	Ford F-Series	584,917
2	Chevy Silverado	415,130
3	Toyota Camry	308,510
4	Nissan Altima	268,981
5	Ford Escape	254,293
6	Ford Fusion	248,067
7	Ram Pickups	244,763
8	Toyota Corolla/Matrix	240,259
9	Honda Accord	235,625
10	Chevy Cruze	231,732

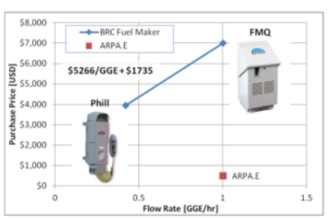
7 of top 10 models represented in these two platforms (76% sales)

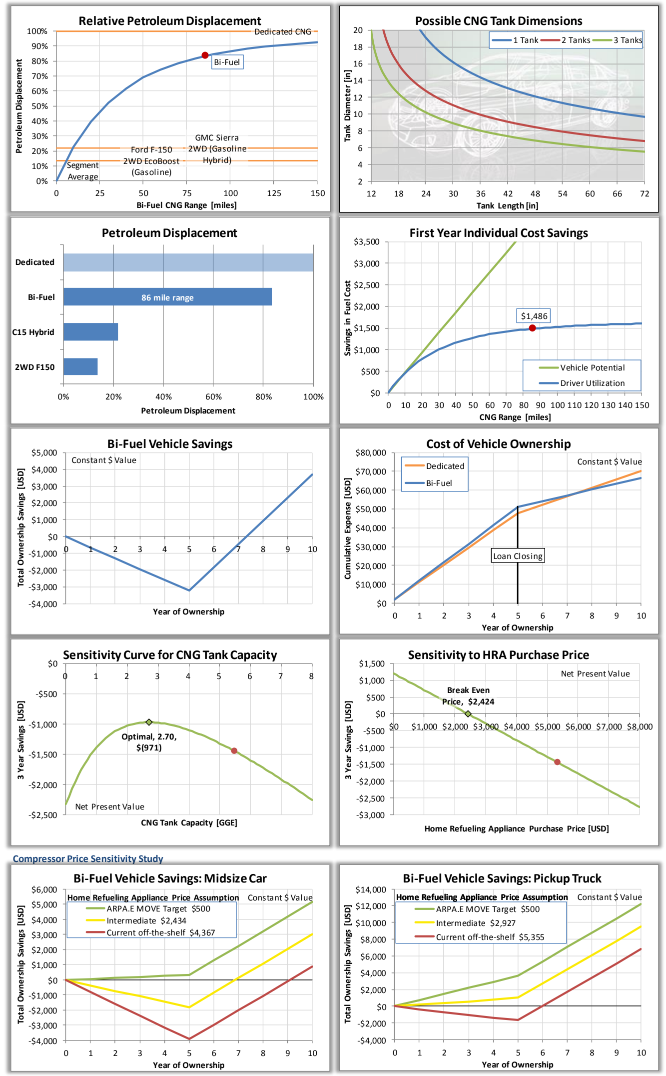
Comprehensive Analysis Spreadsheet Developed to Generate Results

Please Specify Input Values Below

Vehicle Specifications	Inputs	Units		Results	Units
Gasoline Fuel Economy	16.4	MPG	CNG Fuel Economy	15.6	MPG
Vehicle Type	Pickup Truck		Baseline Fuel Economy	16.4	MPG
			Gasoline Conservation	0%	
Baseline Gasoline Volume	26.0	gallons	Estimated Gasoline Range	426	miles
CNG Tank Eq Gallons	5.50	gallons	Estimated CNG Range	86	miles
			Total Range	512	miles
			CNG Tank Volume	83.1	liters
U.S. Fleet Potential					
			CNG Fleet Utility Factor	**83%**	
			Market Potential	20,889,052	vehicles
			Average Daily VMT	32.73	miles
			Annual VMT	11,946	miles
			Annual Gasoline Displacemen	301,830,567	barrels
			U.S. Gasoline Reduction	**-9.4%**	
			Annual CNG Consumption	1.717	scf x 10^{12}
			U.S. Residential CNG Increase	**34%**	
Driver Profile					
Annual VMT	13,500	miles	Individual Utility Factor	87%	
VMT=Vehicle Miles Traveled			Annual Gasoline Miles	1,794	miles
			Annual CNG Miles	11,706	miles
Energy Prices					
Price of Gasoline	$ 4.00	/gal	Annual Gasoline Cost	$ 437.66	
Price of Residential NG	$ 1.39	/gal eq.	Annual CNG Cost	$ 1,148.84	
Federal Road Fuel Tax	$ 0.14	/gal eq.	Annual Compressor Load	1837	kWh
Price of Electricity	$ 0.12	/kWh	Annual Electricity Cost	$ 220.44	
			Fuel Cost Comparison		
			Vehicle Potential	$ 3,969.83	
			First Year Fuel Cost Savings	**$ 1,485.74**	
Vehicle Cost Model					
Base Vehicle Price	$ 24,000				
Insurance & Maintenance	$ 1,000	/year			
			CNG Tank Mass	198	lbs
			CNG Tank Price	$ 752.72	
Balance of System Price	$ 1,526.25				
Home Refueling Appliance Cost Model					
Filling Time	8	hours	Ideal Compressor Flow Rate	0.69	GGE/hr
Installation Price	$ 1,375.00		HRA Purchase Price	$ 5,354.53	*1*
Maintenance	$ 0.20	/gal eq.	Annual Maintenance	$ 150.26	
			Effective CNG Price	**$ 2.02**	/gal eq.
Financial Model					
Down Payment	$ 2,000		Loan Principal	$ 31,009	
Loan Period	5	years			
Loan Rate	3.9%	APR	Monthly Payment	$ 570	
*In Terms of Constant $ Value					
Gasoline Inflation*	0.73%				
Electricity Inflation*	0.03%				
Natural Gas Inflation*	1.22%				
Real Discount Rate	10%		3 Year Savings	$ (1,456)	
End-of-Life Impact					
End-of-Life Mileage	150,000	miles	Years of Service	11.1	years
			Petroleum Displacement	**9,140**	**gallons**
			Lifetime Ownership Savings	**$ 1,824**	







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**

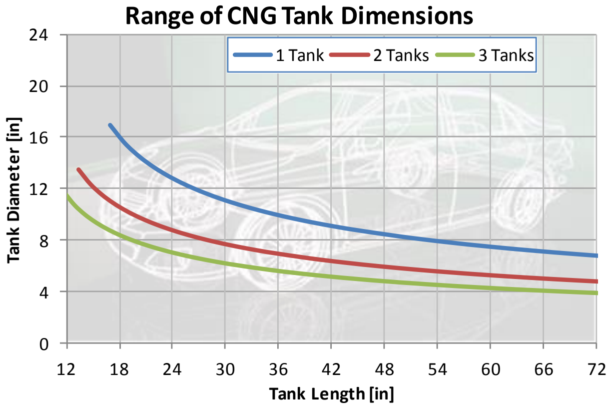
MY 2003 Vehicles		Chevy Cavalier	Ford F-150 2WD	Ford F-150 4WD	GM 2500 2WD
Gasoline					
City fuel econ.	mpg	21	11	11	10
Hwy fuel econ.	mpg	30	15	14	11
Combined fuel econ.	mpg	25.1	12.8	12.4	10.5
Natural Gas					
City fuel econ.	mpg	20	11	10	9
Hwy fuel econ.	mpg	29	14	13	11
Combined fuel econ.	mpg	24.1	12.4	11.4	9.9
Relative econ.		**96%**	**96%**	**92%**	**95%**

www.fueleconomy.gov

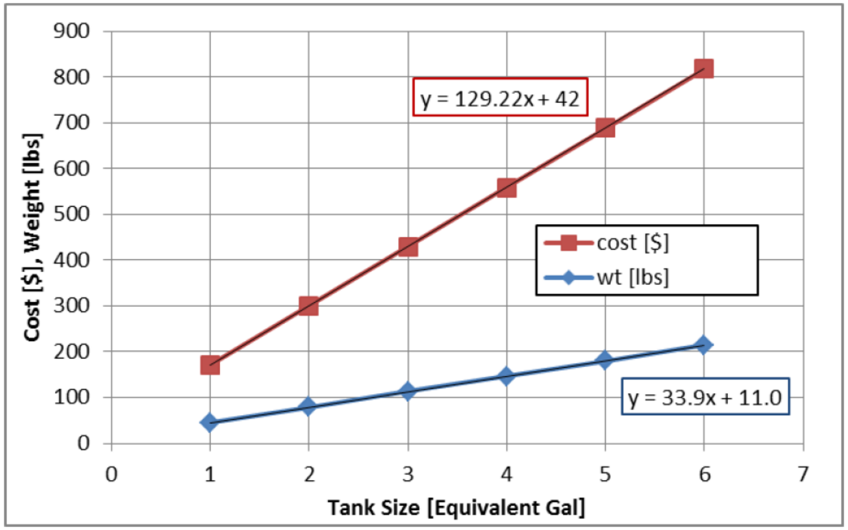
Example Factor: Tank Size and Cost Calculation Tools

- 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

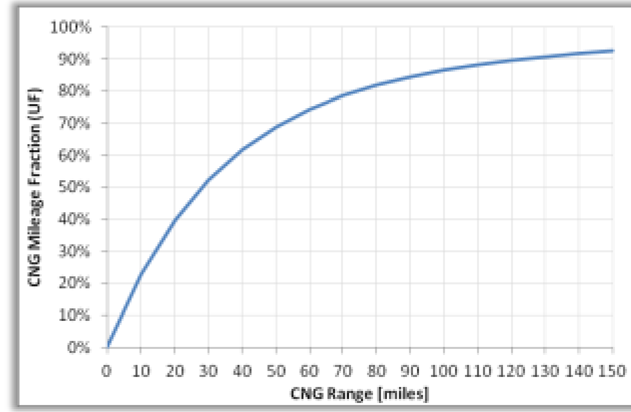


Steel CNG Tank Model Estimating Cost and Weight

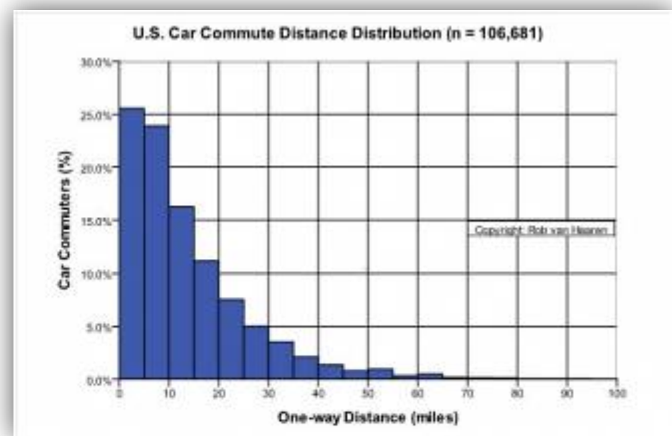


Estimate CNG/Gasoline Use

- 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)

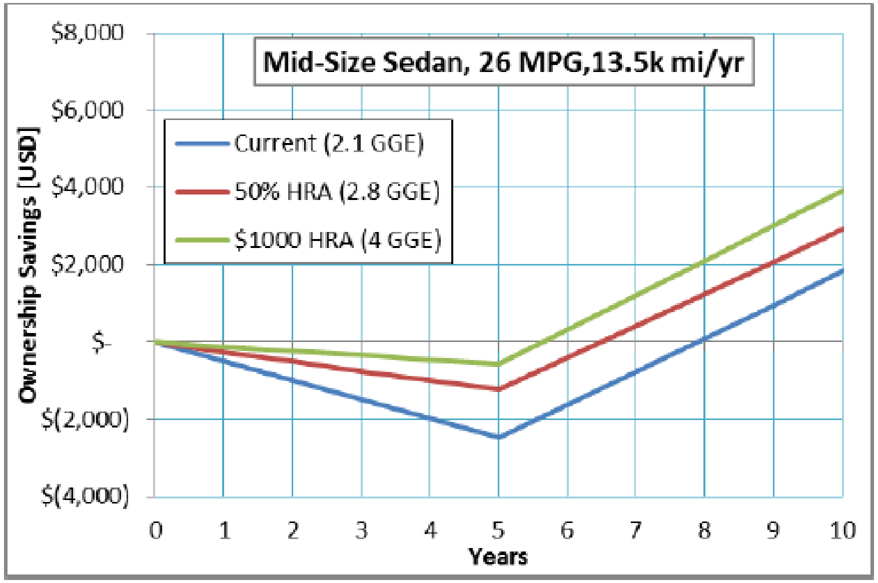
Home Refueling Appliance Cost Model						
Filling Time	8	hours	Ideal Compressor Flow Rate	0.29	GGE/hr
Installation Price	$ 1,375.00		Compressor Price	$ 3,266.02	1
Maintenance	$ 0.20	/gal eq.	Annual Maintenance	$ 132.96	

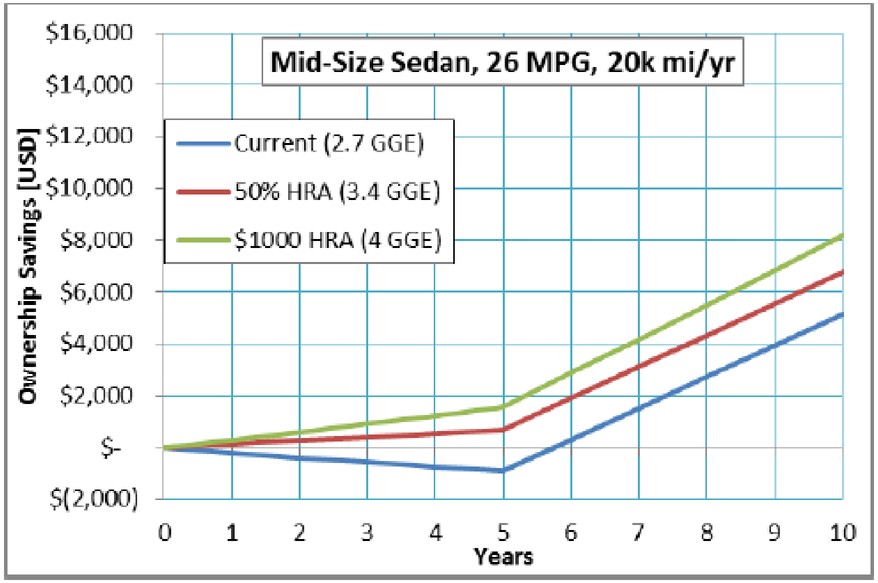
Vehicle Components

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

- If components priced today, costs are much higher
- Realistic supplier costs for 100,000 unit vehicle run
- Commonality of parts likely for cost reductions

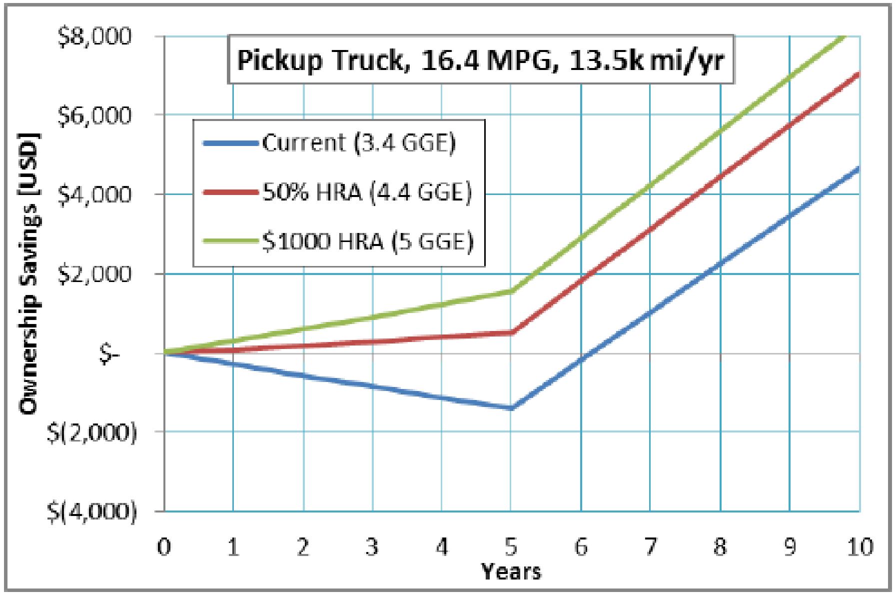
Average Midsize Driver – Variable Home Refueling Appliance (HRA) Payback

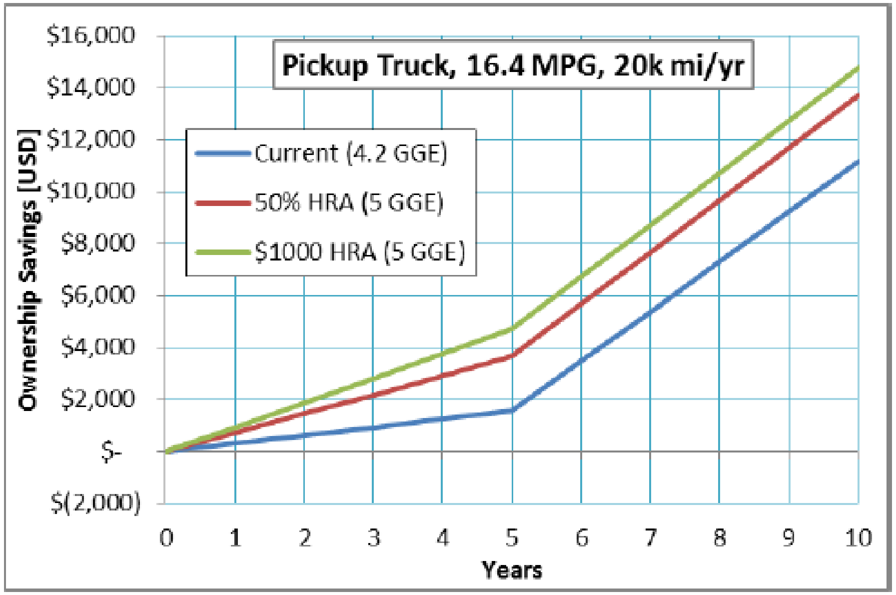




- Savings heavily dependent on mileage traveled per year.

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

HRA Price Reduction Required for Ownership Cost Savings

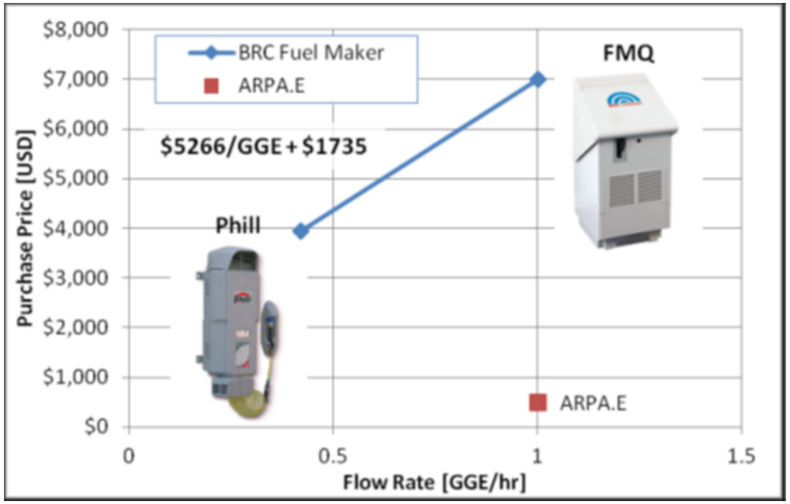
Segment	Average (13.5k mi/yr)	High Miles (20k mi/yr)
Full-Size Pickup	40%	**None**
Mid-Size Sedan	90% (unrealistic HRA price)	30%

- 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

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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