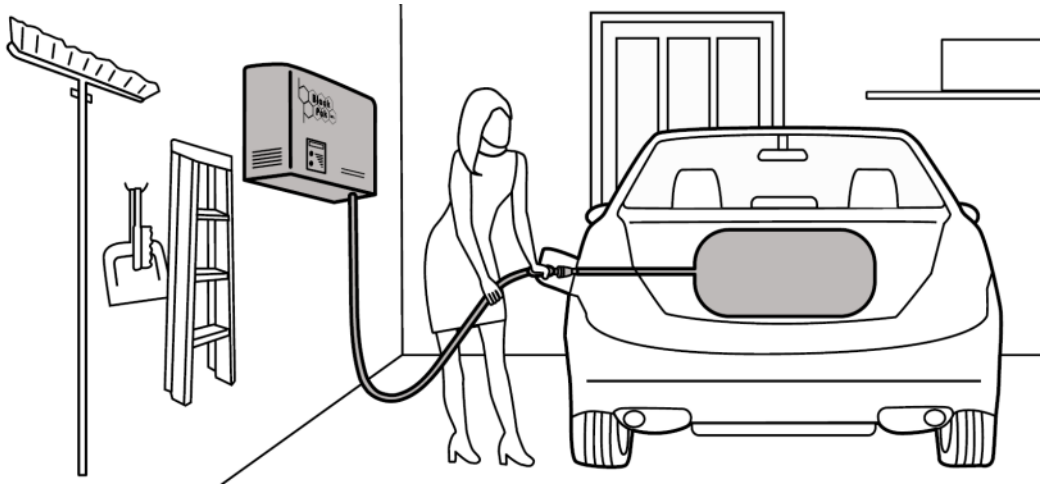
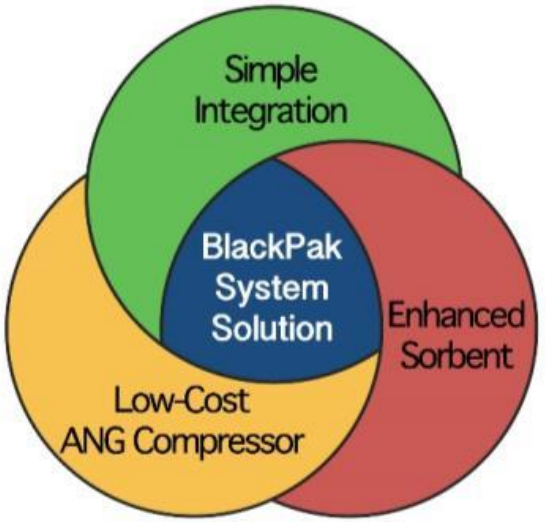
ANG Co-fuel: an economical solution to light-duty natural gas vehicles





www.blackpaktech.com

Economic Drivers

Current and needed cost for the adoption of light-duty natural gas vehicles with at-home refueling*

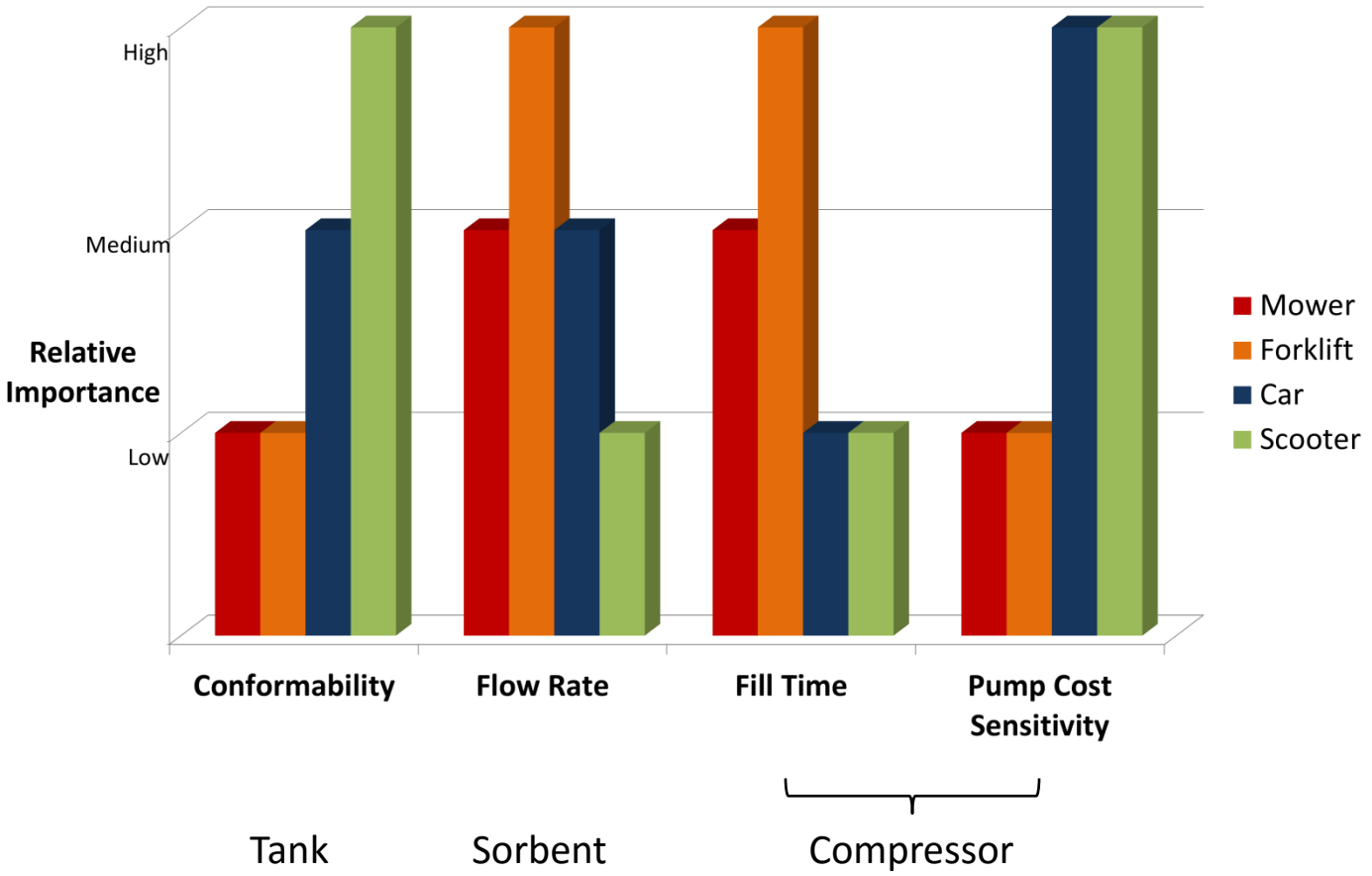
Component	Current	Needed
At-home refueling**	$4000	$500
On-board storage	3500	1500
Balance-of-system	3500	1000
Vehicle installation	1500	1000
TOTAL	**$12,500**	**$4000**

⇒ Only a complete system solution will reach these goals

* From arpa-e Methane Opportunities for Vehicular Energy (MOVE) Funding Opportunity Announcement 2012

** Does not include compressor installation

Other Considerations are Market Dependent



Step 1: At-home refueling $4000 → $1000

Current CNG Compressor Technology

- Fill pressure: 3600 psi
- 3 – 4+ stage unit with CNG-specific compressor block
- Operation: 220 V, 1- or 3-phase circuit
- Price (at-home refueling): $5000 – 10,000
- *Attempts to lower price to <$1000 have so far been unsuccessful*

0.4 GGE/hr

~1.5 GGE/hr

Commercial Refueling Station
40 – 200 GGE/hr,
Cost >$1M

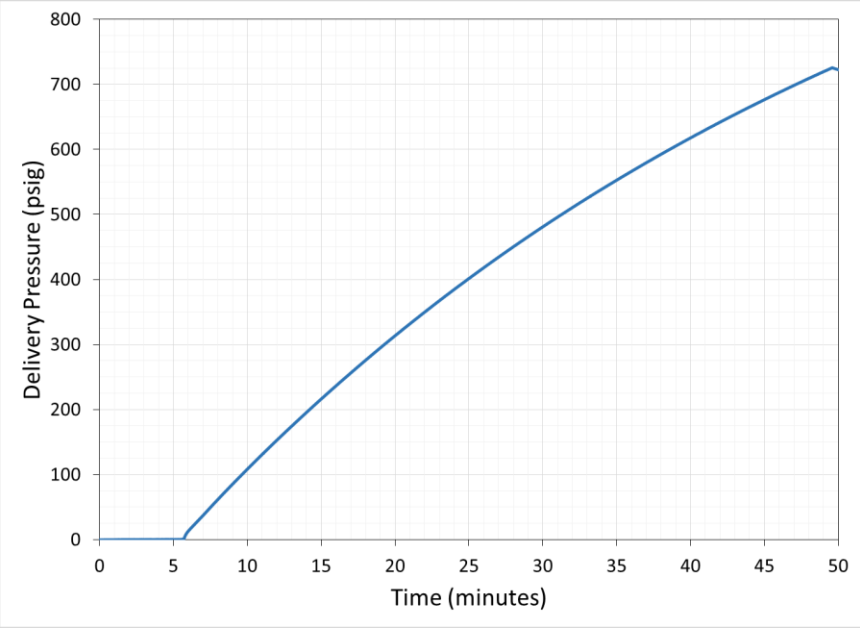
GGE = Gallon of Gasoline Equivalent

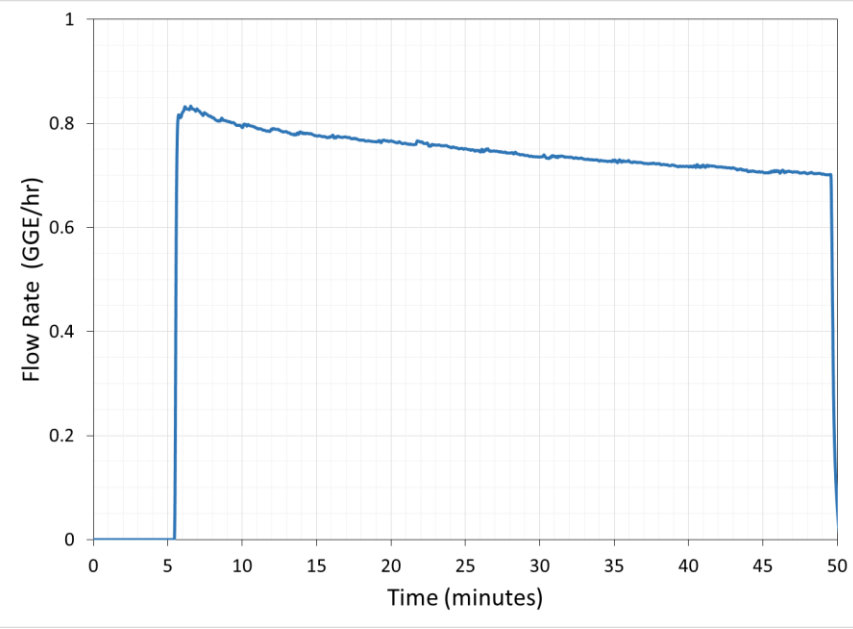
BlackPak ANG Fueling Appliance

- Fill pressure: 500-700 psi
- 2-stage, high volume manufactured compressor block
- Compressor operation optimized for ANG
- Power: 110 V, 15 amp
- Fill rate: 0.7 – 1.5 GGE/hr
- Price: <$1,000 (at volume)

BlackPak ANG Fueling Appliance

- Validated system performance with CO_2 as a surrogate for pipeline natural gas (same specific heat ratio as methane)
  - Delivery pressure: > 700 psig
  - Flow rate: > 0.7 GGE/hr
- BOM and build plan indicate a price <$1,000 *in volume*

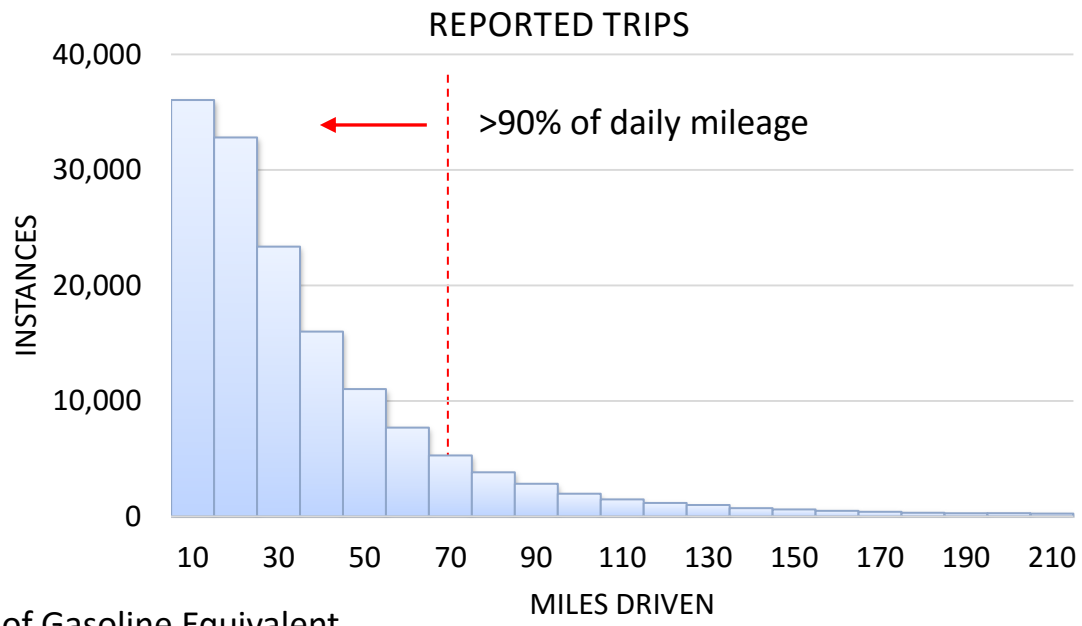




Step 2: On-board storage $3500 → $1500

Decreasing the Cost of On-board Storage (1): Decrease Natural Gas Fuel Tank Size

- Co-fuel: natural gas (NG) and liquid fuel (LF)
  - Operate on 50-90% NG to minimize fuel costs and emissions
  - Automatically switch to LF when NG is exhausted or unavailable
- Allows NG system sizing to optimize economics
  - >90% of all driving days <70 miles (80% <50 miles)
  - 2-5 GGE* tank and compressor leads to lower cost, smaller and more convenient systems

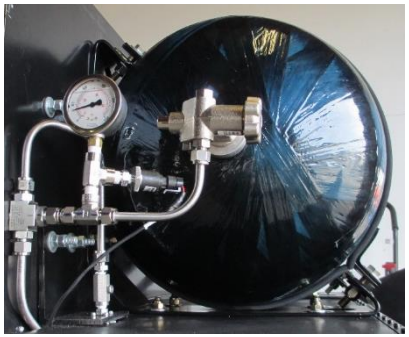


From "Assessment of Electric Cars' Range Requirements and Usage Patterns based on Driving Behavior recorded in the National Household Travel Survey of 2009," van Haaren, July 2012 (data source: NHTS survey 2009).

* GGE = Gallon of Gasoline Equivalent

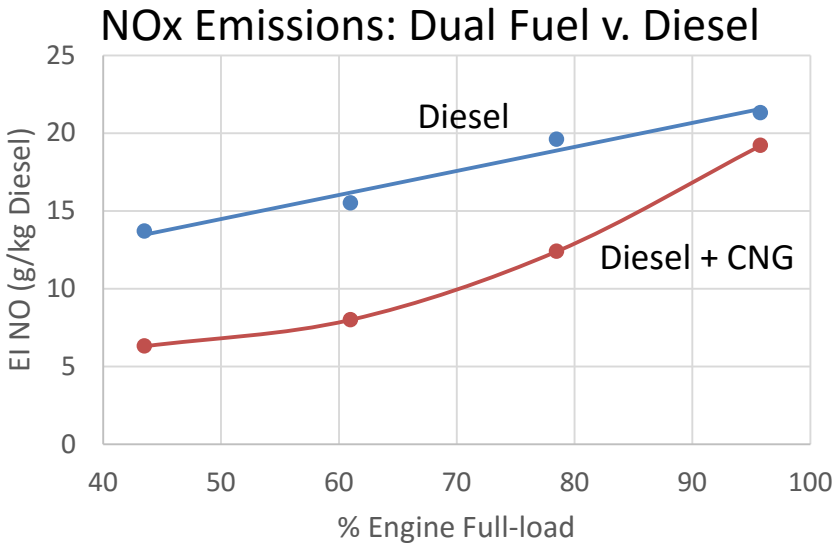
Advantages of Co-fuel Vehicle Operation

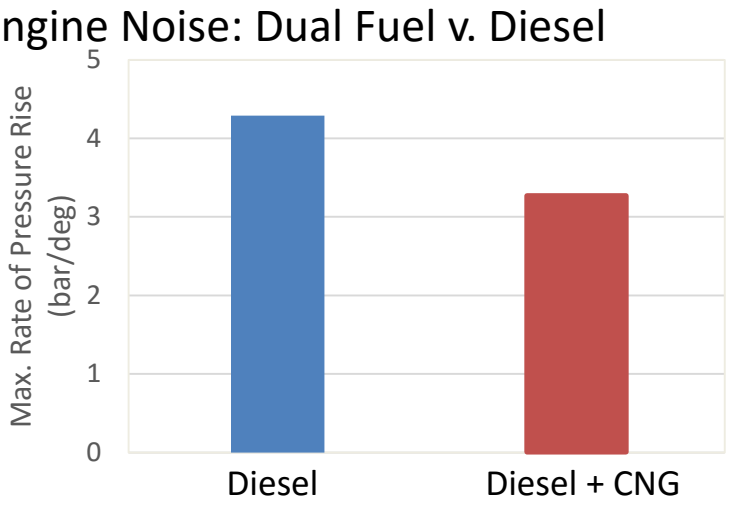
- Operates within standard engine parameters ⇒ simple retrofit / low capital cost
- Optimizes emissions profile
- Smaller tank ⇒ more storage space
  - Toyota Camry:
    - 15.4 ft^3 trunk drops to 9.4 ft^3 with a 2 GGE ANG tank
    - A 10 GGE CNG tank would leave only 1.4 ft^3 trunk
- Eliminates range anxiety
- Substantial fuel savings
- Lower maintenance (natural gas burns cleaner than gasoline)
- Enhanced safety (smaller tank/ and lower pressure v. CNG)

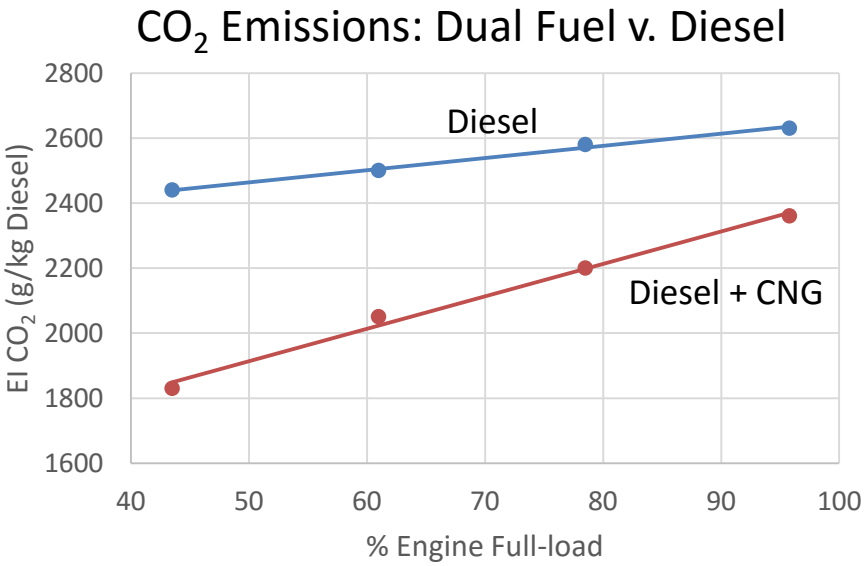


1 GGE tank in trunk of Toyota Camry

Potential for Reduced Emissions from Co-Fuel Operation





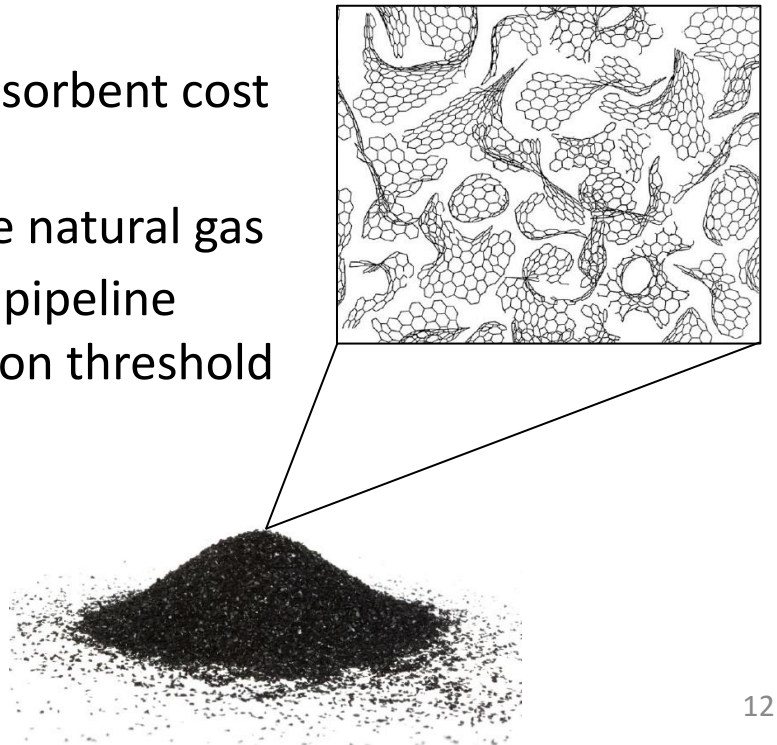


- Dual Fuel operation
  - Generally cleaner than pure diesel
  - May be cleaner than pure NG (less ammonia)

Data from M.M Abdelaal and A. H. Hegab, Energy Conversion and Management 64 (2012) 301

Decreasing the Cost of On-board Storage (2): Compressed to Adsorbed Natural Gas

- Natural gas is adsorbed into the pores of a microporous carbon “sponge”
  - Adsorbed molecules reversibly bond to the pore walls
  - Similar quantity of gas delivered at lower pressure (~500 psi v. 3600 psi for CNG)
- Material characteristics critical
  - Established multiple pathways to carbon sorbent cost <$200/GGE
  - Completed over 1000 cycles with pipeline natural gas
  - Demonstrated adsorption and release of pipeline odorants significantly above odor detection threshold
  - Optimized sorbents for stable capacity using pipeline natural gas

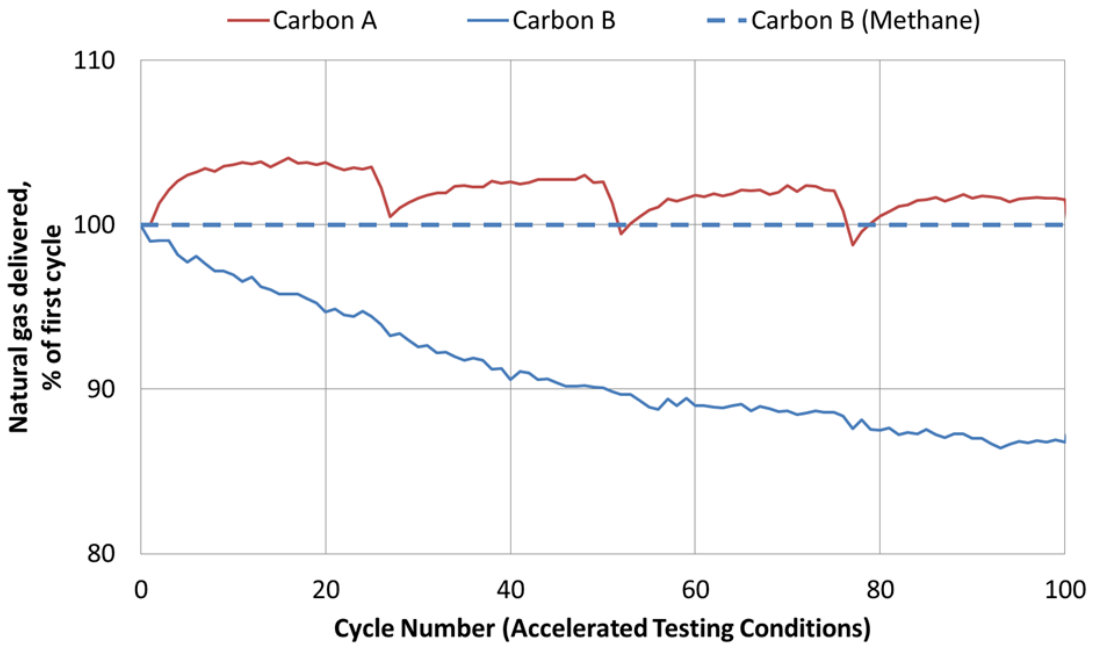


Unique Engineered Sorbent Tuned to Maximize Performance

Lever	Impact
Pore volume	Total storage capacity
Pore size	Time to fill/empty tank
Density	Tank size
Carbon structure	Mechanical strength/robustness Thermal conductivity

Trade-offs

BlackPak's sorbent performance is measured with natural gas – NOT methane



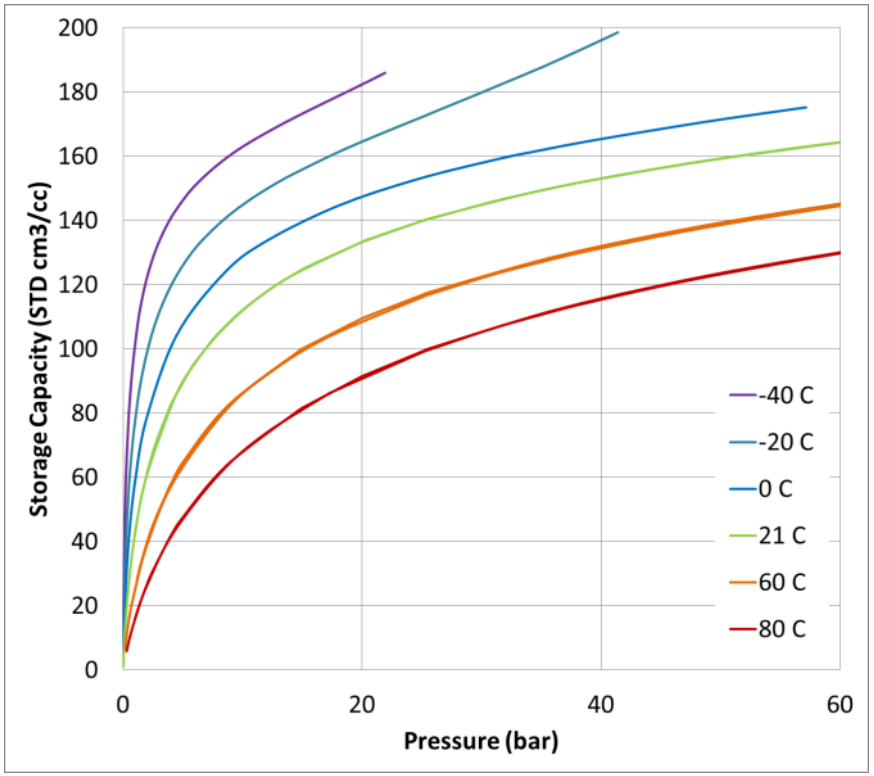
Adsorbed v. Compressed Natural Gas

- Lower pressure ANG (500 psi) v. CNG (3600 psi) enables
  - Lower cost tanks
  - Lower cost compressors
  - Potential for conformal tanks
  - Enhanced safety
- Regulatory issues for ANG
  - Maximum developed pressure is a strong function of temperature

	P @ RT	P @ 80 °C
ANG	500 psi	1450 psi
CNG	500 psi	620 psi
CNG	3600 psi	5285 psi

⇒ ANG systems can use standard 2000 psi CNG tanks with a 3X safety factor

Total Methane Storage on Carbon B



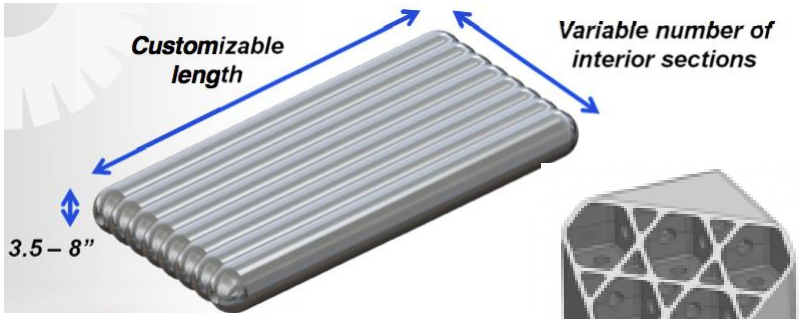
Conformal Storage Tanks

- Given size of co-fuel systems (1 – 5 GGE), conformal tanks are an advantage, but not critical

Toyota Camry – co-fuel (ANG)

Honda Civic CNG (<1/2 cargo volume of standard Civic)

- Conformal tanks will require additional regulatory approval

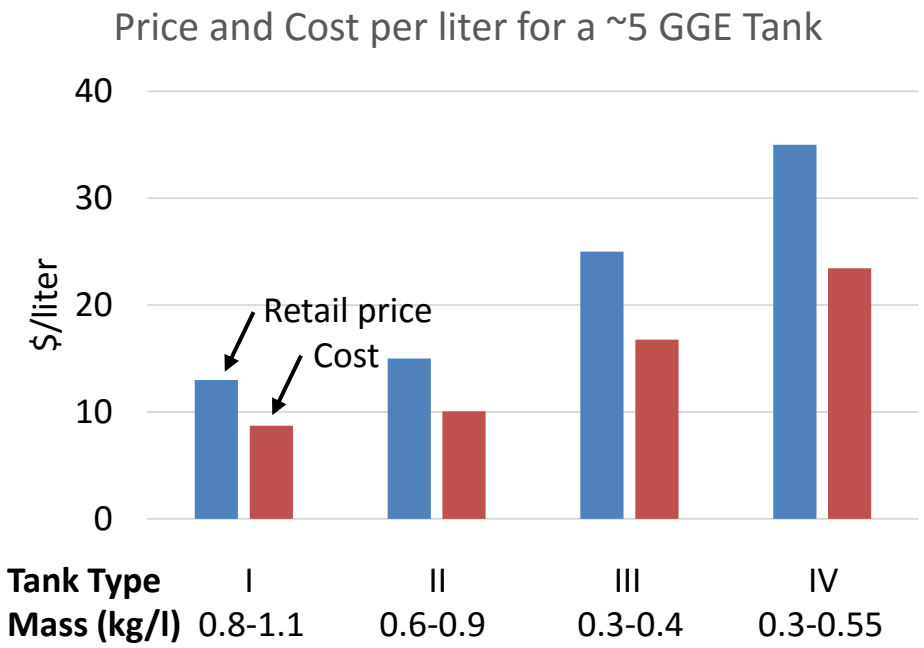


UTRC

REL

Volute

On-board Storage @ $1500



- Sorbent cost
  - $150 – 200/GGE
  - 3 GGE tank
  - ⇒ $450 – $600 for sorbent

- Tank cost
  - Type II tank: $10/liter
  - 90 liter tank
  - ⇒ $900 for tank

- Total cost
  - Tank: $900
  - Sorbent: $450 – $600
  - Total: $1350 – $1500

Step 3: Balance-of-system $3500 → $750

High Cost of Diesel Engine Conversion to CNG

- Diesel engine modifications to assure engine reliability, optimized power, low fuel consumption, and emissions may require:*
  - Improved cooling system efficiency
  - Engine oil cooler

  } Higher compression ratio

  - New valves, valve seats, guides and seals
  - New pistons and rings

  } No lubricity

  - If spark plugs are added, then an ignition system must be installed and cylinder heads modified

- Dual-fuel operation
  - No significant engine modifications required as NG is injected directly into the air intake manifold

* From Omnitek Engineering Corp.

Natural Gas Only Engine Modifications: Honda Civic

- CNG requires modifications to the 1.8-liter four-cylinder engine
  - Stronger connecting rods to handle the added stress of a 12.7:1 compression ratio (up from 10.6)
  - New valves and valve seats that deal with CNG's non-lubricating properties
  - Special fuel injectors
  - Pressure regulator
- Performance
  - 110 hp (30 fewer than gasoline)
  - Torque drops by 22 lb-ft to 106
- Price
  - Increase by ~$7000 (including tank)

Note: similar modifications are required for an F-150 at an estimated cost of $7500 – 9000 (including installation and tank)

Data from Car and Driver Magazine

Benefits of Co-Fuel Platform

- Retrofit will not require engine hardware modification
  - Co-fuel approach keeps engine within standard operating conditions
  - Natural gas is injected into the air intake manifold
  - The engine will operate on liquid fuel when the engine load yields higher temperatures (e.g., high power)
  - The engine will operate on natural gas in the more typical “fuel economy mode”
- Performance
  - Driver not expected to notice any performance changes (demonstrated with a fairway mower)
  - Vehicle will switch from natural gas to liquid fuel automatically when there is a sudden driver demand for power (e.g., passing cars) or when natural gas cannot accommodate the demand for power (e.g., highway on-ramp acceleration)

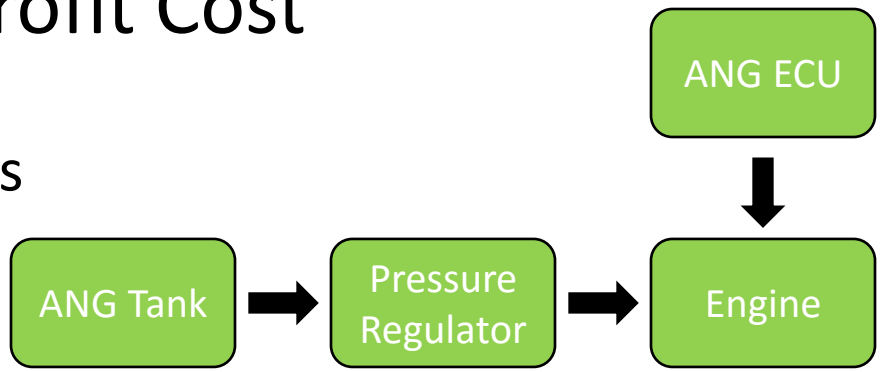
Step 4: Vehicle installation $1500 → $750

Vehicle Installation: Toyota Camry

- System designed for natural gas/gasoline co-fuel operation
- 2 GGE ANG tank installed in vehicle trunk
- Natural gas injectors installed directly into intake manifold
- Commercial CNG pressure regulator modified for ANG operation
- Baseline emissions data collected ⇒ converted vehicle must pass ULEV standards

Vehicle Retrofit Cost

- Retrofit kit of major components provided by BlackPak



- Estimated retrofit installation cost

Labor Description	Est. Time [hrs]	Cost [$] (est. $80/hr)
ANG tank mounting	2	160
ANG tank plumbing	1.25	100
Intake manifold swap	3.2	256
Regulator installation	.25	80
Regulator to engine plumbing	1.5	120
ANG ECU mounting	.25	20
ECU harness modification	1	80
TOTAL	**8.2**	**756**

Plan Forward

Market Opportunities

Platform	Approximate TAM ($BN)
Lawn mowers	0.3
Generator sets	1.2
Forklifts	2.8
Light-duty trucks	200
Passenger vehicles	300

Increasing TAM

Increasing cost pressure

Increasing regulatory hurdles

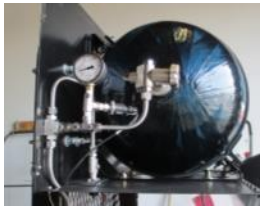
Beachhead market: *golf course mowers*

- 15,500 US courses (2012) with ~50% in CA, FL, and TX
- ~100 acres/course mowed almost daily
- Annual fuel budget between $30,000 and $100,000/course
- $150-300M TAM with <12 month return
- Reduced regulatory hurdles compared to light duty vehicles

Vehicle Installation: Fairway Mower

- Concept (technology) demonstration at Monarch Bay Golf Course
  - Retrofit standard Toro platform with 3 GGE ANG tank and commercial compressor
  - 300+ hrs of field operation by industry staff – no change to engine performance
  - Characterize real-world usage requirements
    - Fuel-savings-driven payback period currently at 16 mos.
    - Additional performance optimization is ongoing

Monarch Bay mower retrofit



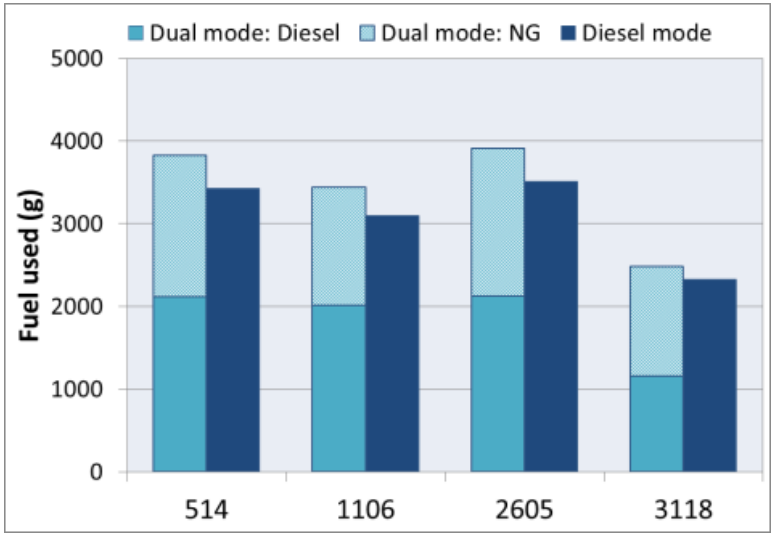
Video of mower in operation at www.blackpaktech.com

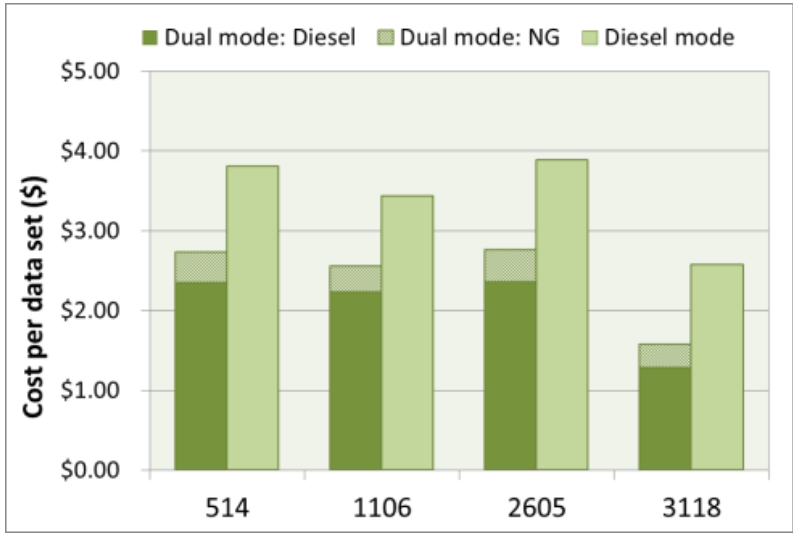
Fairway Mower Performance

- Minimal Engine modifications and no change in engine performance

Metric	Dual-fuel Mode	Diesel-only Mode
Engine RPM	3190	3070
MAP	133 kPa	130 kPa
EGT	347 °C	350 °C

- Liquid fuel at high power demand reduces the stress on the NG system, increases drivability, and limits the effects of the higher combustion temperatures

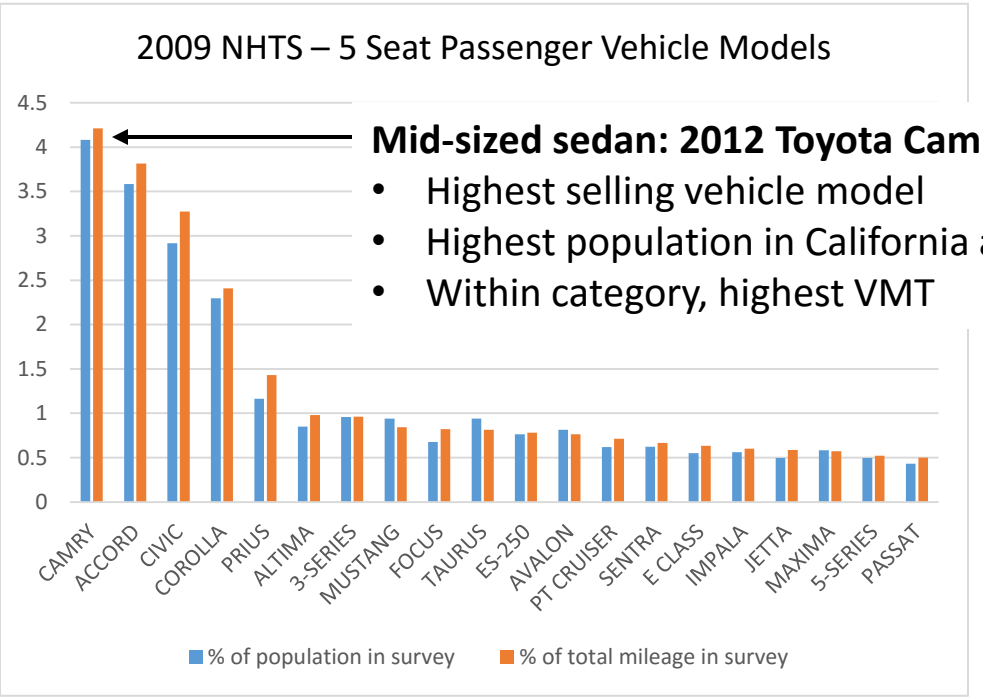




CEC Program Overview

Leverage knowledge gained from arpa-e MOVE program and apply to light duty vehicles

- Vehicle model selected with highest impact potential on the reduction of fossil fuel use based on
  - California and National Household Travel Survey (NHTS) data
  - Vehicle model population, vehicle miles traveled (VMT)
  - Vehicle category analysis: five-seat passenger cars have the largest percentage of both vehicle population and VMT



Mid-sized sedan: 2012 Toyota Camry (2.5L)

- Highest selling vehicle model
- Highest population in California and nationwide
- Within category, highest VMT

From Technology Development to On-road Implementation

- Focus on retrofit market
  - Beachhead market: commercial mowers
  - Expansion into forklifts and scooters
  - Prototype development for light-duty vehicles
- Business model
  - Numerous approaches with a goal of minimizing customer risk while maximizing customer benefit and adoption rate
  - Develop partnerships with golf course management companies, leasing companies, ANG materials and components suppliers, natural gas suppliers, and financing partners
- Regulatory compliance is a driver of implementation plan
  - Regulations affect the cost of implementation AND the cost of installation
  - Need to address issues at the national and local levels
    - Non-uniform implementation of national “guidelines”…

Regulatory Compliance

- Clear path for mower certification: 2 years and $550,000+
  - Near-term: certifications via BlackPak specific Special Projects with CSA
    - 1st Special Project opens 65% of the golf-course mower fleet to retrofit
    - 2nd Special Project opens small commercial refueling appliance
  - Longer-term: revise regulations for streamlined certifications
- Path for automotive certification: higher risk, cost, and unknown timeline
  - Near-term: certifications via BlackPak specific Special Projects with CSA
    - Limited applicability: new Special Project per make, model, and year-range
    - Limited payback potential for a narrow range of platforms
  - Longer-term: revise regulations for streamlined certifications
- Installation requirements for refueling systems differ substantially by locale
  - Need a uniform **standard** - not guidelines
  - Is what happened with solar installation a good guide?

California ANG Road Vehicle Adoption

- Add low pressure fill nozzle to NGV 1 (2017)
  - Needed to safely work alongside CNG filling
- Update ANG tank testing for NGV 2 (2019)
  - Address small differences to ensure vehicle safety
- NFPA 52 requires NGV 1 and NGV 2 equipment
- CA Motor Vehicle code follows NFPA 52
- CARB and EPA treat all NGV technologies equally
- Work with CEC to communicate to CHP and CARB

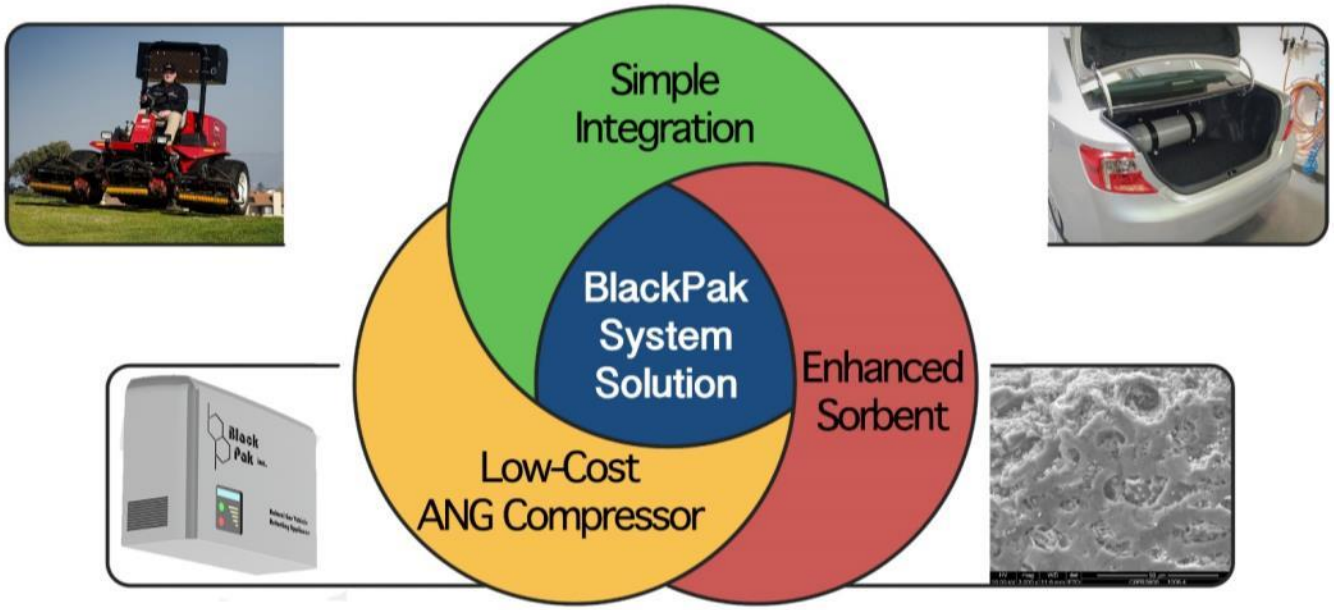
California Fueling Appliance Adoption

- To enable broad market adoption…starting with CA
  1. Update NFPA 52 (2016) and NFPA 54 (2017) to adopt NGV 5.1 (2015)
  2. Define RFA as an appliance in NFPA 54 (2017)
  3. Update CMC (**2019**) to adopt NFPA 54 (2017)
     - Simplifies installation requirements
  4. Update CFC (**2019**) to adopt NFPA 54 (2017) and point to CMC for RFA installation
     - Moves installation requirements from fire code to mechanical code
  5. Work with CEC to communicate changes and processes to local authorities
- This covers only a minority of states –
  - CA follows NFPA 54
  - Majority states follow international code

BlackPak: A Systems Solution to Natural Gas Storage and Delivery

arpa-e MOVE Program			BlackPak	
Component	Current	Needed	Pricing	Enabling Technology
At-home refueling	$4000	$500	$1000	Low-cost, low-pressure ANG-specific compressor
On-board storage	3500	1500	1500	Low pressure ANG and co-fuel operation (<5 GGE tank)
Balance-of-system	3500	1000	750	Co-fuel operation (with standard commercial-off-the-shelf engines)
Installation	1500	1000	750	Co-fuel operation (no major engine mods)
TOTAL	**$12,500**	**$4000**	**$4000**	

Project Funding



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