METHANE – THE PERFORMANCE FUEL
92% of transportation powered by petroleum

60% of transportation fuel is finished motor gasoline (including ethanol), mainly used in cars and light trucks

3% of transportation powered by natural gas

Fuel used for U.S. transportation, 2014

- gasoline (petroleum): 56%
- diesel (petroleum): 22%
- jet fuel (petroleum): 11%
- other: 3%
- natural gas: 3%
- biofuels: 5%

Note: Due to rounding, data may not sum to exactly 100%.

Source: U.S. Energy Information Administration, Monthly Energy Review (March 2015), Tables 2.5 and 3.8c, preliminary data
Natural gas is only viable fuel replacement for transportation petroleum that has required scale.

Renewable fuel pathway by substituting up to 100% biomethane.

Why have we surrendered 60% of the transportation sector reliant on gasoline?

Paradigm Shift Required for Light Duty

CNG – The low cost fuel
“less for more”
“compromise”

Methane – The performance fuel
“more for less”
“advantage”

- Reduced fuel costs
- Reduced emissions
- Less performance than gasoline and diesel
- Lower efficiency
- Compromised utility
- Price premium

- Reduced fuel costs
- Reduced emissions
- More performance than gasoline and diesel
- High efficiency
- Same or better utility
- Price advantage
1. Advanced powertrains that fully exploit ultra high-octane low-carbon fuel properties of methane
   a. Not been done to-date – missed opportunity
   b. High efficiency and high performance at the same time – outperform gasoline and diesel
   c. >30% CO2 reduction TTW* (up to 90% with biomethane WTW)

2. Conformable CNG tanks and low cost gas compression (e.g. ARPA-E MOVE Program)

3. Phase 2 EPA/NHTSA rules (2017-25)
   a. Become particularly challenging starting in 2021 for light trucks
   b. Conventional gasoline and diesel increasingly challenged
   c. Electrification is an option, but adds cost and may not be preferred approach for certain market segments

* Compared with advanced gasoline engines
Deep CO2 Reductions Starting 2021

Figure 1-4 CO2 (g/mile) Light-Truck Standard Curves

2017-20
2021-25

Full Size Pickup Truck (extended cab)
We Have Seen A Complete Market Shift Before

» In 1950 diesel powered trucks cost more and were heavier than gasoline trucks, yet the market shifted 100% to diesel within 2 decades. Why?

» A new paradigm of high productivity with low operating costs meant fleets needed to make the change or go out of business.

» The same 100% shift happened a decade earlier in locomotives; steam to diesel.

» Signs of a market shift to natural gas are appearing (e.g. refuse truck segment).

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1. MacKay & Co., & Wards Auto Group, a division of Penton Media, Inc.
2. ACEA
3. Westport
Diesel Cars in Europe – Then and Now

Diesel cars in the 1980’s

All about fuel cost savings
< 5% market share

Diesel cars today

All about performance with added benefit of low CO2 and fuel costs
> 50% market share
Consequences of VW’s Actions

Volkswagen’s falsification of pollution tests opens the door to a very different car industry

Sep 26th 2015 | The Economist From the print edition

“…Some fear that this may be the “death of diesel”. So be it. There is still scope to improve the venerable petrol engine; and to switch to cleaner cars that run on methane, hydrogen and electricity, or are hybrids. A multi-billion-dollar race is already under way between these various technologies, with makers often betting on several of them as the way to meet emissions targets.”
CNG Passenger Cars – Now and Future

CNG Cars Today

- All about fuel cost savings
- < 5% market share

Advanced Methane Cars Tomorrow

- All about performance with added benefit of low CO2 and fuel costs
- > 50% market share
CNG Pickup Trucks – Now and Future

CNG Pickups Today

- All about fuel cost savings
- < 5% market share

Advanced Methane Pickups Tomorrow

- All about performance with added benefit of low CO2 and fuel costs
- > 50% market share
Industry Megatrend: PFI to Turbo GDI
Global Passenger Cars and Light Trucks

(Source: Continental Fact Book 2014)
Fuel Economy & Performance are Driving the Global Shift to Turbo GDI

2015 Chevrolet Silverado C15 2WD

- Gasoline Vehicle
- 5.3 L, 8 cyl, Automatic 6-spd
- MSRP: $26,105 - $47,875

2015 Ford F150 Pickup 2WD

- Gasoline Vehicle
- 2.7 L, 6 cyl, Automatic (S6), Turbo
- MSRP: $25,800 - $51,650

2015 Ram 1500 2WD

- Diesel Vehicle
- 3.0 L, 6 cyl, Automatic 8-spd, Turbo
- MSRP: $25,660 - $49,980

Regular Gasoline

- **19** combined city/highway
- 5.3 gal/100mi
- **16 23** city highway

- **22** combined city/highway
- 4.5 gal/100mi
- **19 26** city highway

- **23** combined city/highway
- 4.3 gal/100mi
- **20 28** city highway

---

Source: U.S. DOE and EPA  http://www.fueleconomy.gov/
Fuel Economy & Performance are Driving the Global Shift to Turbo GDI

<table>
<thead>
<tr>
<th>Jan 30, 2015</th>
<th>2015 Chevrolet Silverado 1500 LTZ Z71</th>
<th>2015 Ford F-150 Lariat 4x4</th>
<th>2014 Ram 1500 Outdoorsman EcoDiesel 4x4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>POWERTRAIN/CHASSIS</strong></td>
<td>Front-engine, 4WD</td>
<td>Front-engine, 4WD</td>
<td>Front-engine, 4WD</td>
</tr>
<tr>
<td><strong>DRIVETRAIN LAYOUT</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ENGINE TYPE</strong></td>
<td>90-deg V-8, aluminum block/heads</td>
<td>Twin-turbo 60-deg V-6, iron block/alum heads</td>
<td>Turbodiesel 60-deg V-6, iron block/alum heads</td>
</tr>
<tr>
<td><strong>VALVETRAIN</strong></td>
<td>OHV, 2 valves/cyl</td>
<td>DOHC, 4 valves/cyl</td>
<td>DOHC, 4 valves/cyl</td>
</tr>
<tr>
<td><strong>DISPLACEMENT</strong></td>
<td>325.1 cu in/5,328 cc</td>
<td>164.4 cu in/2,694 cc</td>
<td>182.3 cu in/2,988 cc</td>
</tr>
<tr>
<td><strong>COMPRESSION RATIO</strong></td>
<td>11.0:1</td>
<td>10.0:1</td>
<td>16.5:1</td>
</tr>
<tr>
<td><strong>POWER (SAE NET)</strong></td>
<td>355 hp @ 5,600 rpm*</td>
<td>325 hp @ 5,750 rpm</td>
<td>240 hp @ 3,600 rpm</td>
</tr>
<tr>
<td><strong>TORQUE (SAE NET)</strong></td>
<td>383 lb-ft @ 4,100 rpm*</td>
<td>375 lb-ft @ 3,000 rpm</td>
<td>420 lb-ft @ 2,000 rpm</td>
</tr>
</tbody>
</table>

**TEST DATA**

**ACCELERATION TO MPH, UNLADEN; TOWING 7,000-LB TRAILER**

<table>
<thead>
<tr>
<th></th>
<th>2015 Chevrolet Silverado 1500 LTZ Z71</th>
<th>2015 Ford F-150 Lariat 4x4</th>
<th>2014 Ram 1500 Outdoorsman EcoDiesel 4x4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-30</td>
<td>2.3; 5.7 sec</td>
<td>2.4; 5.0 sec</td>
<td>2.6; 5.2 sec</td>
</tr>
<tr>
<td>0-40</td>
<td>3.5; 8.9</td>
<td>3.5; 7.5</td>
<td>4.3; 9.0</td>
</tr>
<tr>
<td>0-50</td>
<td>5.2; 13.6</td>
<td>4.9; 11.5</td>
<td>6.3; 14.5</td>
</tr>
<tr>
<td><strong>0-60</strong></td>
<td>6.9; 19.5</td>
<td>6.5; 16.2</td>
<td>8.8; 23.9</td>
</tr>
<tr>
<td>0-70</td>
<td>9.4; -</td>
<td>8.6; 22.2</td>
<td>11.8; -</td>
</tr>
<tr>
<td>0-80</td>
<td>12.2; -</td>
<td>11.2; -</td>
<td>16.0; -</td>
</tr>
<tr>
<td>0-90</td>
<td>15.5; -</td>
<td>14.2; -</td>
<td>20.8; -</td>
</tr>
<tr>
<td>PASSING, 45-65 MPH</td>
<td>3.6; 15.5</td>
<td>3.2; 9.4</td>
<td>5.1; 21.2</td>
</tr>
<tr>
<td><strong>QUARTER MILE</strong></td>
<td>15.4 sec @ 89.8 mph; 22.0 sec @ 62.3 mph</td>
<td>15.1 sec @ 92.8 mph; 20.7 sec @ 68.0 mph</td>
<td>16.6 sec @ 81.5 mph; 22.2 sec @ 58.7 mph</td>
</tr>
<tr>
<td><strong>DAVIS DAM &quot;FRUSTRATION&quot;</strong>**</td>
<td>7.6 sec, 665 ft</td>
<td>6.0 sec, 524 ft</td>
<td>9.0 sec, 812 ft</td>
</tr>
</tbody>
</table>

Technology MegaTrend Enables Methane – The Performance Fuel

Global Passenger Car / Light Truck Market

New technology
Future emissions regulations
Best Value for End Customer

Shift to downsized, turbocharged SI DI engines

Impact for NGV Industry:

- Future NGVs will increasingly be based on turbo GDI platforms that must:
  - a. operate without damaging GDI fuel system (i.e. when using PFI natural gas) or
  - b. replace GDI fuel system with CNG DI – can exceed performance of gasoline
- Turbo GDI have limitations in fully exploiting methane’s fuel properties
CNG DI can exceed GDI Base Engine Performance

Engine full load performance with and without CNG DI optimized turbocharger and resulting time-to-torque comparison for Ford EcoBoost 1.0L engine using CNG DI system

Progression of Methane Powertrain Technology - Outperform Petrol, Diesel

1. **Common.** Prior generation. Degraded performance relative to petrol.


3. **Better.** Delphi, Conti and Bosch developing NG DI FIE. Exceeds petrol performance and efficiency.

4. **Best.** Westport is developing. Outperforms petrol & diesel.

* Petrol co-fueling required in NG mode.
Technology Trend
Convergence b/w Gasoline & Diesel

» New gasoline & diesel engine families designed with common elements for high boosting with 0.5 l per cylinder with common block, bore, stroke, bore centers, etc. and shared machining & assembly lines:
  ▪ BMW’s new modular Efficient Dynamics at Hams Hall, UK
    https://www.press.bmwgroup.com/usa/download.html?textId=161119&textAttachmentId=198820
  ▪ Volvo’s Drive-E engine family at Skövde, Sweden
  ▪ Jaguar Land Rover’s new Ingenium engine family at Wolverhampton, UK

» Convergence trend ideal for fully exploiting ultra-high octane performance fuel properties of methane

» Higher cylinder pressure capability of diesel bottom end needed due to higher compression ratio and advanced combustion phasing with methane

» Gasoline engine elements such as cam phasing, ignition system, etc needed for Otto cycle combustion
Enhanced Spark Ignited Technology

» September 2014, Westport unveiled its proprietary enhanced spark ignited engine technology
» First time SI NG engine exceeds diesel engine performance
» Redesign, optimization and downsizing provide significant fuel economy improvements
» Stoichiometric operation with EGR and simple 3-way catalyst
» ~ 15% engine + aftertreatment product costs savings vs diesel
Enhanced Spark Ignited Technology
System Elements

- Optimized in-cylinder air motion
- New head packaged within base diesel engine envelop
- Improved thermal management
- Lower peak cylinder pressure than diesel
- EGR for knock mitigation & improved efficiency
- Multi-point fuel injection & high energy ignition
- Carryover diesel bottom end for robust product
- Improved airflow distribution cyl-to-cyl
- Simpler piston

*Westport engine test data from a modern Brand X 7.XL diesel donor engine
Base diesel peak output @ 23 bar BMEP
Enhanced SI NG peak output > 25 bar BMEP
Current production state-of-the-art diesel-derived on-road NG SI engines 19-21 bar BMEP
Example: Ram 1500

3.0L ECODIESEL DOHC V-6

Displacement: 2,500 cc
Block / head material: Compacted graphite iron / aluminum
Horsepower (SAE net): 240 @ 5,000 rpm
Torque: 420 lb.-ft. (570 Nm) @ 2,000 rpm
Specific output: 80 hp/L
Bore x stroke: 83 x 92 mm
Compression ratio: 15.5:1
EPA city / highway: 30 / 38 mpg
Assembly site(s): Trento, Italy
Application tested: 14 Ram 1500 EcoDiesel
Additional applications: 14 Grand Cherokee

Source: Ward's Auto

ESI NG engines avoids expensive diesel:
1. Aftertreatment (DPF and SCR)
2. Fuel injection equipment
3. Multi-stage variable geometry turbocharging
2 stage turbocharger system (VGT & WG) on diesel can be replaced with single WG turbocharger

Example Concept Study: new medium duty diesel

Turbo for Current Diesel Engine
Enhanced Spark Ignited Technology
Boosting System Example

» 2 stage turbocharger system (VGT & WG) on diesel can be replaced with single WG turbocharger

Example Concept Study: new medium duty diesel

Turbo for NG Enhanced SI Solution
Optional Range Extension Mode

» Methane DI combined with petrol PFI offers knock tolerance / octane enhancement

» Reserve some methane for operation in range extension mode with majority of operation and fuel burned being gasoline (e.g. 75% gasoline / 25% methane)

» Gasoline tank in the 4-7 gallon range (similar size to DEF tank)

Illustration based on 26.5mpg, 75% gasoline usage in range extension, and 4 to 7 USgal gasoline tank. May need to limit 196 litre range to 450 miles due to Phase 2 EPA/NHTSA rules.
Methane Opportunities for Vehicular Energy

MOVE

Dane Boysen, Ph.D.  Program Director
Jason Rugolo, Ph.D.  Program Director
Sven Mumme, MBA  Tech-to-Market Advisor
Mark Pouy, Ph.D.  Technical Consultant

Improving Performance: Advances in Pumps, Fill, and Range
North American Natural Gas Vehicle Conference and Expo
Denver, CO  |  September 16th, 2015
if it works... will it matter?

“if it works”
1. make science into technology
2. take risks industry won’t
3. identify new opportunities

“matter”
1. reduce energy imports
2. improve energy efficiency
3. reduce energy emissions
<table>
<thead>
<tr>
<th></th>
<th>Now</th>
<th>Need</th>
<th>How</th>
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<tbody>
<tr>
<td><strong>Home Refueler</strong></td>
<td>$5000</td>
<td>$1500</td>
<td>—</td>
</tr>
<tr>
<td>compressor</td>
<td>1500</td>
<td>500</td>
<td>MOVE</td>
</tr>
<tr>
<td>system balance</td>
<td>2500</td>
<td>750</td>
<td>volume</td>
</tr>
<tr>
<td>installation</td>
<td>1000</td>
<td>250</td>
<td>volume</td>
</tr>
<tr>
<td><strong>Vehicle</strong></td>
<td>$8000</td>
<td>$2500</td>
<td>—</td>
</tr>
<tr>
<td>onboard storage</td>
<td>2500</td>
<td>1500</td>
<td>MOVE</td>
</tr>
<tr>
<td>system balance</td>
<td>4000</td>
<td>750</td>
<td>volume</td>
</tr>
<tr>
<td>certification</td>
<td>2500</td>
<td>250</td>
<td>regulation</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$13000</td>
<td>$4000</td>
<td>—</td>
</tr>
<tr>
<td><strong>Payback</strong></td>
<td>15 y</td>
<td>5 y</td>
<td>—</td>
</tr>
</tbody>
</table>
2010 Honda Civic GX – Natural Gas
63% of volume wasted

9.3 MJ/L at 3600 psi
-> 5.8 MJ/L
REL, Inc.

jason.rugolo@hq.doe.gov
Otherlab/Volute

Loss
Material
Volume

jason.rugolo@hq.doe.gov
Otherlab/Volute
United Technologies Research Center

1220mm
[48.00”]

600mm
[23.63”]

133mm
[5.25”]

jason.rugolo@hq.doe.gov
Democratize Re-fueling

From ~ 1,500 stations to...

CNG Fuel Stations

64 million potential fueling locations.

Natural Gas Meter Locations

vs ~180,000 gasoline station
Over 20 M€ in Gov’t Funding in Europe for Advanced Methane Powertrains

- GAS-ON Project (European funding of 17 M€, total budget 23 M€, 2015-2018)
  - Innovative injection, ignition and boosting system concepts
  - Advanced exhaust gas aftertreatment system
  - Detecting the gas-quality and its composition
  - Fiat (CRF), Ford, VW, Renault, Delphi, Conti + 13 others

- Bosch led consortium with Daimler (German Gov’t funding of 3.8 M€, 2015-2017)

Bosch-led Consortium Explores CNG’s “Greater Potential” as Vehicle Fuel

Direct injection for CNG engines: more efficiency, more driving enjoyment

In Germany, a consortium of automotive suppliers and automakers led by Robert Bosch GmbH is striving to develop a new fuel system for Compressed Natural Gas (CNG) that may well be a gamechanger for the industry. The design concept takes the principle of direct injection, normally associated with diesel and gasoline engines, and applies it to natural gas, thereby making the already lower-emission natural gas vehicle (NGV) even more economical and eco-friendly.
DOE VTO SuperTruck Project

» $115M of funding from DOE (3 projects)

» Projects started in 2010

» Goal was to improve freight efficiency by 50%
Proposed SuperPickupTruck Project ($50M from DOE?)

Stream 1: nearer term, lower risk
1. Low cost home refuelling
2. Lower cost, lighter conformable CNG tanks (3600 psi)
3. High efficiency, high performance powertrains

Stream 2: longer term, higher risk, but higher reward
1. Self-refueling vehicles (designed into engine)
2. Adsorbed NG (reduce pressures for above to be more viable)
3. Conformable lower pressure tanks to contain the ANG
4. High efficiency, high performance powertrains

Innovation is a delicate thing. Stop nurturing too early and it will die. Avoid the valley of death.
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VP, Business Development
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