Technology Choices for Existing and Up and Coming New Applications of Natural Gas as Transportation Engine Fuel

Patric Ouellette, CTO
Westport Innovations

September 24, 2012
Agenda

- Westport
- Natural Gas as a transportation fuel Today
- Gas Engine Technology Spectrum
- SI Technology for Passenger Cars and Light-Duty Trucks
- SI Technology for Medium-Duty and Medium Heavy-Duty Commercial Vehicles
- HPDI for Heavy Heavy-Duty On-Highway Trucks
- Non Road Mobile High Horse Power Applications
Westport at a Glance

**Market Focus**
Leading the global shift from petroleum fuels to natural gas for transportation

**Position**
Strong first mover advantage with unmatched IP, relationships, market coverage, products, capabilities

| Caterpillar | Electro Motive |
| Cummins     | General Motors |
| Kenworth    | Weichai Power  |
| Peterbilt   | Volvo          |

**Opportunity**
Immediate profitable expansion from where we are; colonize new territory in light duty; offroad
Global Operations

Total Global Employees: 945
Downward Pressure on Natural Gas Prices

Natural gas price projections are significantly lower than past years due to an expanded shale gas resource base.

As more information has become available on the size of shale gas resources, EIA’s projections of future NG prices have fallen.

**ABUNDANT: HUGE GLOBAL GAS RESOURCES**

Gas resources are plentiful, growing and geographically diverse.

- Conventional and unconventional recoverable gas resources can supply >250 years of current global gas production.
- Unconventional gas is transforming the global gas market.

<table>
<thead>
<tr>
<th>Region</th>
<th>Remaining Recoverable Resources (TCM)</th>
<th>Equivalent in Years of Current Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>404.5</td>
<td>130</td>
</tr>
<tr>
<td>Unconventional</td>
<td>380.5</td>
<td>123</td>
</tr>
<tr>
<td>Total</td>
<td>785</td>
<td>253</td>
</tr>
</tbody>
</table>

Source: Shell Technology Forum, Sept 2012, IEA World Energy Outlook, Wood Mackenzie, Shell Interpretation
Natural Gas Vehicle Market at a Tipping Point*

* In Economics, the point at which a dominant technology or player defines the standard for an industry—resulting in "winner-take-all" economies of scale and scope.

Global NGV Population
(millions of natural gas vehicles)

26% average annual growth rate

U.S. Retail Fuel Prices
(dollars per diesel gallon equivalent)

sources: IANGV and Clean Cities Alternative Fuel Price Report
Infrastructure - North America

CNG Fueling Station Count

LNG Fueling Station Count

Sources: DOE Alternative Fuel Data Center
Example of LNG Infrastructure Build-Out
Planned Clean Energy Retail Locations

- 150 fuelling stations planned
- Approximately 70 anticipated to be open in 33 states by the end of 2012
- Balance (~80 more) in 2013.
- Many will be co-located at Pilot-Flying J Travel Centers already serving goods movement trucking.

Sources: Clean Energy
## Transportation Technology Spectrum

<table>
<thead>
<tr>
<th>Application</th>
<th>Engine Displacement</th>
<th>kW/cyl</th>
<th>Fuel / Year</th>
<th>Current Uptake</th>
<th>Fuel Choice</th>
<th>Current Gas Technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Large marine</strong></td>
<td>Up to 25,000 L</td>
<td>Up to 1,000</td>
<td>Up to 30,000,000 L</td>
<td>~100</td>
<td>LNG</td>
<td>dual fuel, SI pre-chamber, direct injection</td>
</tr>
<tr>
<td><strong>Off-highway</strong></td>
<td>Up to 1,000 L</td>
<td>~100,000 L</td>
<td>~100,000 L</td>
<td>~0</td>
<td>LNG</td>
<td>n/a</td>
</tr>
<tr>
<td>Off-highway vehicles</td>
<td>9 to 16 L</td>
<td>~75</td>
<td>~100,000 L</td>
<td>~10,000</td>
<td>LNG or CNG</td>
<td>direct injection, dual fuel, spark ignited, Stoichiometric, Lean-burn</td>
</tr>
<tr>
<td>Heavy-duty vehicles</td>
<td>5 to 9 L</td>
<td>~40</td>
<td>~40,000 L</td>
<td>~100,000</td>
<td>LNG or CNG</td>
<td>MD spark ignited, Lean-burn, Stoichiometric, Stoichiometric+EGR</td>
</tr>
<tr>
<td>Medium-duty vehicles</td>
<td>5 to 9 L</td>
<td>~40</td>
<td>~40,000 L</td>
<td>~100,000</td>
<td>LNG or CNG</td>
<td>MD spark ignited, Lean-burn, Stoichiometric, Stoichiometric+EGR</td>
</tr>
<tr>
<td>Light-duty vehicles</td>
<td>5 to 9 L</td>
<td>~40</td>
<td>~5000 L</td>
<td>&gt;1,000,000</td>
<td>CNG</td>
<td>LD spark ignited</td>
</tr>
<tr>
<td></td>
<td>Up to 7 L</td>
<td>~40</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Values are coarse estimates and information is based on Westport’s best knowledge.
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- Non Road Mobile High Horse Power Applications
Passenger Cars and Light-Duty Trucks

Spark ignition (SI) technology is well suited for **passenger cars** and **light-duty trucks**

- Easiest approach when adapting gasoline engines
- Most passenger cars and LD trucks are spark ignited gasoline engines
- Most commonly configured as bi-fuel operation today
- Fitted to CNG or LPG fuel systems
Changing Global Requirements....

- From 2016 for pass car, 2017 for Light Truck, regulated targets will be adjusted according to actual vehicle mass to bring average to 130g/km - Ramped-in penalties for non-compliance thereafter
- EPA/NHTSA GHG/FC rule for passenger car and smaller light duty truck kicking in 2016
Light Duty Engine Trends

- Engines continue to be aggressively downsized in Europe (e.g. 1.0 litre Ecoboost)
- NA and Turbo Petrol DI have been coming to North America
- Many engines have now VVA

These represent …interesting… challenges for NG fuel systems integration, in particular for aftermarket retrofit or even for zero mile upfit
Natural Gas CO₂ benefits but performance shortfall?

- CNG offers CO₂ benefits
- Expect that most US CNG LD truck models will rate very well on CO₂ with a range of 200-300 miles
- Recent Argonne study indicates 2% fuel efficiency (mpg) penalty for same displacement, 12% penalty for same 0-60mph performance
- Seeing example of engine “upsizing”
  - Opel Zafira Touring – 1.4l turbo petrol vs. 1.6l turbo CNG
  - Supercharging can offset the deficit (e.g. VW Ecofuel)
Storage

- Integrated composite tanks
- Reduced size gasoline tanks

DOE ARPA-E MOVE
(Methane Opportunities for Vehicular Energy)

<table>
<thead>
<tr>
<th>Energy Density</th>
<th>[MJ/L]</th>
<th>[MJ/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel</td>
<td>37.3</td>
<td>46.2</td>
</tr>
<tr>
<td>Gasoline</td>
<td>34.2</td>
<td>46.4</td>
</tr>
<tr>
<td>LNG (-162 °C)</td>
<td>22.2</td>
<td>50</td>
</tr>
<tr>
<td>CNG (250 Bar)</td>
<td>9.2</td>
<td>50</td>
</tr>
<tr>
<td>CNG + Type I</td>
<td>7.4</td>
<td>5.9</td>
</tr>
<tr>
<td>CNG + Type IV</td>
<td>7.4</td>
<td>15.6</td>
</tr>
<tr>
<td>ANG (35 bar)</td>
<td>9.2</td>
<td>12</td>
</tr>
</tbody>
</table>

sources: DOE ARPA-e MOVE Program
SI Technology for MD and MHD Vehicles

SI Technology is a good compromise in refuse trucks, transit buses, delivery trucks, etc.

- Cost-effective method to use natural gas
- Well suited to CNG or LNG
- Achieves low emissions with passive exhaust after-treatment

CR < 11.5
SI Technology for MD and MHD Vehicles

Westport JVs integrate fuel system components, ignition system with advanced electronic controls on modified base diesel engines to provide industry-leading engines

- Electronically controlled Lean Burn
- Stoichiometric Cooled EGR

Shanqi LNG Truck with WWI WP12NG380 LB Engine
CWI Combustion Technology
Spark Ignited Stoichiometric with Cooled EGR

Stoichiometric EGR
Three Way Catalyst
Architecture

Key difference with automotive engines

Applications
• Average loads are higher
• Efficiency matters at higher loads
• Reliability and durability expectations

Architecture
• Base engine is diesel
• Firing pressures are higher
• Some constraints on air motion/piston shape
Differences:
Cummins ISX12 diesel and CWI ISX12 G natural gas

<table>
<thead>
<tr>
<th></th>
<th>ISX 12</th>
<th>ISX 12G</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Performance</strong></td>
<td>310-425 hp</td>
<td>320-400 hp</td>
</tr>
<tr>
<td></td>
<td>1150-1650 ft-lb</td>
<td>1150-1450 ft-lb</td>
</tr>
<tr>
<td><strong>Torque at idle</strong></td>
<td>800 ft-lb</td>
<td>700 ft-lb</td>
</tr>
<tr>
<td><strong>Exhaust Emissions Control</strong></td>
<td>DPF+SCR</td>
<td>Three Way Catalyst</td>
</tr>
<tr>
<td><strong>Engine Brake</strong></td>
<td>380 hp</td>
<td>240 hp</td>
</tr>
</tbody>
</table>
SI Technology for MD and MHD Vehicles

HD Rule EPA - DOT (NHTSA)
HD Engines CO$_2$ Emissions Standards

- 8.5% LHD/MHD
- 5.0% HHD
- 6.0% MHD Tractor
- 4.2% MHD Tractor

Sources: EPA, Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles, NRC
Fuel Storage Choice – LNG / CNG

• Desired vehicle range
  – Ideally same as diesel
  – Vehicle chassis space a premium

• Infrastructure availability
  – CNG leading, but many legacy LD focused
  – >150 Public LNG Stations in 2013

• Fuel Costs
  – CNG has slight advantage
  – Both provide savings over diesel

• Ease of Use
  • LNG fill speeds same as diesel
  • Slower CNG fills may be acceptable for some fleets

<table>
<thead>
<tr>
<th></th>
<th>CNG Net 125 DEG</th>
<th>LNG Net 125 DEG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective DEG</td>
<td>155</td>
<td>140</td>
</tr>
<tr>
<td>Weight Penalty over diesel</td>
<td>2500 lbs</td>
<td>1100 lbs</td>
</tr>
<tr>
<td>Space Penalty over diesel</td>
<td>x 6</td>
<td>x 2</td>
</tr>
</tbody>
</table>
Dual Fuel Engine Technology

- Engine that can operate under diesel or diesel-gas mode
- Diesel-gas mode is diesel ignition of pre-mixed gas
- Engine is diesel engine, and new engines must be certified as a diesel engine (and also as a gas engine)
- Engine not optimized for natural gas operation which is compromised at low and high operating loads
  - Methane emissions are a challenge for emissions compliance
- Implementation reported to offer between 50% and 75% substitution
- Retrofit Opportunities
- Technology not currently offered by Westport
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Direct Injection Engine Technology

Direct Injection is ideally suited for heavy-duty (HD) trucks and high-horsepower (HHP) applications (e.g. locomotives, large mining trucks)

• Only technology that maintains full diesel torque and cycle efficiency while providing high diesel substitution
The Westport HD System

- Cummins ISX base engine platform
- Compression ignition
- Direct injection high pressure natural gas
- High diesel substitution (up to 95%)
- Liquefied Natural Gas (LNG) fuelled heavy-duty engine
- Diesel Engine Performance remains
- EPA/CARB 2010 certified
- DPF/SCR-equipped
## Applications Today

<table>
<thead>
<tr>
<th>ADR 02</th>
<th>ADR 03</th>
<th>EPA 2007</th>
<th>EPA 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 400 kW (550 hp)</td>
<td>• Development in Progress</td>
<td>• 330 kW (450 hp)</td>
<td>• Cooled EGR, DPF, SCR</td>
</tr>
<tr>
<td>• 2500 N-m</td>
<td>• Cooled EGR + DPF</td>
<td>• 2375 N-m</td>
<td>• 4% BSFC improvement</td>
</tr>
<tr>
<td>• 24 bar BMEP</td>
<td>• Maintain GHG benefit</td>
<td>• 21 bar BMEP</td>
<td>• Maintain/increase GHG benefits</td>
</tr>
<tr>
<td>• Cooled EGR</td>
<td></td>
<td>• Cooled EGR + DPF</td>
<td></td>
</tr>
<tr>
<td>• Peak Efficiency 44.4%</td>
<td></td>
<td>• Peak Efficiency 42%</td>
<td></td>
</tr>
<tr>
<td>• Cruise Efficiency 43.3%</td>
<td></td>
<td>• Cruise Efficiency 41.8%</td>
<td></td>
</tr>
<tr>
<td>• BSFC benefit ~ 5%</td>
<td></td>
<td>• NOx benefit 33%</td>
<td></td>
</tr>
<tr>
<td>• GHG benefit &gt;25%</td>
<td></td>
<td>• GHG benefit &gt;20%</td>
<td></td>
</tr>
</tbody>
</table>
Case Study: Vedder Transport

- Largest fleet in BC – high environmental commitment
- 50 new Peterbilt 386s with Westport HD 15L
- Hauling milk/food products, waste & wood chips in dedicated service
- 3500 tonne annual GHGe reductions from implementation
- Cost reductions result in ~16 month payback
While EPA does not regulate CH4 emissions, it is assumed here that nmHC/CH4~0.15

In this area NOx strategy changes and CH4 becomes increasingly a challenge.
Effect of EGR on unburned methane
1200 RPM, 8.5 Bar, Gas Rail Pressure of 20 MPa
50% IHR at 5, 10 and 15 ATDC
Methane Oxidation Quenching - CFD

![Graph showing bulk averaged temperature over CA ATDC with Methane Oxidation and Diesel Oxidation Cut-off Temperatures indicated.]
Methane Oxidation Quenching - CFD

Effect of gas injection pressure on unburned methane

Mode 13 (7.9 Bar, 1800 RPM) , HiP = 195 bar, LowP = 100 bar

CH4g is unburned methane from bulk gases quenching, CH4w is from wall quenching
Impact of Injection Pressure - 6 Cyl. Engine

Effect of Injection Pressure on unburned methane
Mode 7 (4.9 bar, 1200 RPM), Mode 13 (7.9 bar, 1800 RPM)
CH4g is unburned methane from bulk gases quenching, CH4w is from wall quenching
Where is the PM coming from?

- Black Carbon content in PM measured using filters, light-scattering instruments
- BC concentrations increase with load, addition of EGR
- Contribution of NG to BC PM evaluated using $\text{C}^{14}/\text{C}^{12}$ isotope ratio
- Majority of the BC is from NG
- With higher PM (higher load, EGR) more PM is from NG
NOx - PM trade-off

- Reductions in NOx achieved with EGR come at the expense of increased PM.
- Delaying combustion (delaying both gas and diesel injections) can also reduce NOx.
  - But impacts fuel efficiency.
- Optimal trade-off between GISFC, PM, and NOx emissions as a function of timing, EGR level.
  - Equivalent to conventional diesel combustion.
Continuing HPDI Improvements

- **Higher torque/horsepower capability**
  - Higher torque and horsepower used in Australia for several years
  - Achieved through higher flow injectors and engine calibration

- **Emissions after-treatment improvements**
  - Westport HD 15L engine uses identical after-treatment as diesel engine, despite reduced engine out emissions
  - Westport evaluating options to exploit cleaner-burning properties of natural gas to simplify emissions control equipment
  - Several identified strategies are being validated in our laboratories
Continuing Changes

Source: Commercial Vehicle Innovation Summit, Sept 2011
Exploring New Market Opportunities

- Mine haul trucks
- Industrial locomotives
- Tugboats
## Significant High-Horsepower Opportunities

<table>
<thead>
<tr>
<th>target vehicles</th>
<th>current issues</th>
<th>engine OEMs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MINING</strong> (RESOURCE EXTRACTION)**</td>
<td>mine haul trucks</td>
<td>2bn gal of diesel consumed annually by the top 10 mining companies alone(^1) with 28,600 large mine haul trucks (&gt;100 ton capacity) operating around the world(^2) 2,035 onshore drilling rigs working in U.S. and Canada(^3) with estimates of the pressure pumping horsepower in North America set to top 10mn hp in 2011(^4)</td>
</tr>
<tr>
<td><strong>RAIL</strong></td>
<td>diesel mainline freight locomotives</td>
<td>Rail industry consumes 9bn gal of diesel fuel annually, half of this in North America(^5) Fuel represents approximately 24% of US railroad operating costs(^6)</td>
</tr>
<tr>
<td><strong>MARINE</strong></td>
<td>ferries tugboats PSVs work and crew boats</td>
<td>Marine industry consumes 13bn gal of diesel fuel annually(^5) Emissions reduction in sensitive coastal and inland waterways are a priority Some examples of LNG ferries and platform support vessels (PSV) in Scandinavia, but no widespread adoption yet</td>
</tr>
</tbody>
</table>

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1. Westport analysis
2. Morgan Stanley/Parker Bay
3. Baker Hughes report, August 2010
4. United Holdings investor information presentation 2011
5. UN Energy Statistics Database 2008
Tier 4 Emissions

EPA Locomotive Standards
Line Haul

EPA Non Road Standards
> 750 HP
### US - EPA Emissions Legislation (g/kWh)

<table>
<thead>
<tr>
<th>Engine Class</th>
<th>Start year</th>
<th>Cycle</th>
<th>Size</th>
<th>NOx</th>
<th>NMHC</th>
<th>CO</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD On-highway</td>
<td>2010</td>
<td>FTP</td>
<td>&gt; 14000 lb</td>
<td>0.27</td>
<td>0.19</td>
<td>21</td>
<td>0.013</td>
</tr>
<tr>
<td>Locomotive (line haul)</td>
<td>2015</td>
<td>1033.53</td>
<td>&gt; 750 kW</td>
<td>1.7</td>
<td>0.19</td>
<td>2.0</td>
<td>0.04</td>
</tr>
<tr>
<td>Marine (Category 1/2)</td>
<td>2014-2017</td>
<td>ISO 8178</td>
<td>&lt; 3700 kW</td>
<td>1.8</td>
<td>0.19</td>
<td>5.0</td>
<td>0.04</td>
</tr>
<tr>
<td>Mobile non-road</td>
<td>2015</td>
<td>ISO 8178</td>
<td>&gt; 560 kW</td>
<td>3.5</td>
<td>0.19</td>
<td>3.5</td>
<td>0.04</td>
</tr>
</tbody>
</table>

THC requirements of ~1 to 1.9 g/kW-hr
Part Load Efficiency is very important in Locomotive Applications.
# Technologies profile

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Spark-Ignited or Pilot Ignited Lean Burn Premixed</th>
<th>Dual Fuel</th>
<th>High Pressure Direct Injection</th>
</tr>
</thead>
</table>
| Benefits | • No DPF/No SCR for Tier 4  
• Well understood  
• Full Substitution | • Full Operation under diesel mode  
• Full performance and efficiency  
• No change to base engine | • No DPF/SCR for Tier 4  
• 90% substitution  
• Low HC emissions  
• Full performance and efficiency  
• No changes to base engine  
• Limited limp home |
| Drawbacks | • Part load efficiency  
• HC emissions  
• Very tight A/F ratio control needed to maintain emissions and performance  
• No limp home  
• Significant changes to base engine | • Limited substitution  
• HC emissions  
• Full Tier 4 diesel emissions system | • Requires some in-cylinder NOx reduction  
• High Pressure Fuel System required |
Tender Car?

LNG Transport Already Common

Special consideration for fueling locomotive however

- Needs to be coupled with locomotive
- Could be standard well car and ISO tank
- May need to fuel locomotives with different powertrains
- Multiple alternative configurations of rail car, tanks, coupling
Conclusions

- Conditions are set for an increased in availability in NG engines, and for volumes to increase.
- This opens opportunities for greater investment in NG engine technologies, including more optimization specific to gas:
  - Several OEMs already building platforms that are better suited for gas.
- Continuing evolution of petrol and diesel platforms means that NG technology must find ways to adapt.
Thank You

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