Mark Dunn,
Westport Innovations

OPTIMISED NATURAL GAS ENGINES FOR
PHASE II GHG COMPLIANCE
Westport Fuel Systems Brands and Market Breadth
Large Scale Shifts in Fuel Selection Can Occur

1. MacKay & Co., & Wards Auto Group, a division of Penton Media, Inc.
2. ACEA
3. Westport
Introduction

» The HD GHG 1 rule (2014 to 2017) broke new ground in 2011
  ▪ 3 main categories: pick up trucks and vans, vocational vehicles and tractor trailers
  ▪ Different test methods, cycles and limits according to the segment

» New GHG 2 final rule covers 2021 to 2027
  ▪ More integrated approach for engines and vehicles in Class 4 and above
  ▪ Allows engine benefits to be transferred to the vehicle in new ways

» Under GHG 2, natural gas can provide engine and vehicle compliance benefits

» The market for natural gas is strong in some segments such as refuse trucks and transit bus but we need to target larger segments such as HD pickups and Class 8 trucks to make a bigger impact
Heavy Duty Pickup Trucks (Class 2b/3) Opportunity

» Class 2b/3 is the largest heavy-duty segment in terms of sales volumes.

» NG options are available but they have limited appeal:
  ▪ Less than gasoline performance
  ▪ Diesel-like price premium.
  ▪ Load bed space is taken up with CNG storage.

» The issues can be addressed with suitable engine and CNG storage approaches.

» Addressing the HD pickup opportunity requires the combination and improvement of light and medium duty SI NG engine approaches.

Option prices relative to gasoline today:
- Diesel: $8,600 – $9,300
- CNG: $9,500 - $11,000

Figure 2. New 2012 heavy-duty vehicle registrations by class and fuel type (Polk, 2013)
The Class 2b-3 Vehicle Challenge

Electrification and hybridization is beneficial for smaller vehicles but difficult to implement economically in heavy-duty pick ups.

Figure 1. Commercial pickup and van work factor-based CO\textsubscript{2} regulatory targets and agencies’ estimated average CO\textsubscript{2} for gasoline and diesel pickups and vans.
Progression of Natural Gas Technologies in Light Duty Space

Common. Current/prior generation. Slightly degraded peak power & torque relative to gasoline.
Problem - Static view of CNGV Potential

» GREET model assumes that CNGV engine technology is almost static compared with improving SI DI engines

» 5% efficiency gap widens to 12% with introduction of more efficient SIDI engines (most likely downsized assumed)
Progression of Natural Gas Technologies in Light Duty Space

1. Gasoline NA PFI engines with NG PFI
   - Common. Current/prior generation. Slightly degraded peak power & torque relative to gasoline.
   - *Gasoline co-fueling and other protection countermeasures required in NG mode.

2. Turbo Gasoline DI engines with NG PFI

* Gasoline co-fueling and other protection countermeasures required in NG mode.
2 Turbo DI Engines Produce More Compelling CNG Vehicles

**V90 Bi-Fuel Specification**

<table>
<thead>
<tr>
<th>Engine</th>
<th>T5 Bi-Fuel. Four-cylinder, turbo-charged Drive-E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque</td>
<td>350 N·m</td>
</tr>
<tr>
<td>Max Output</td>
<td>254 hp</td>
</tr>
<tr>
<td>Transmission</td>
<td>8 speed Geartronic auto</td>
</tr>
<tr>
<td>Cylinder Capacity</td>
<td>1969 cm³</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Consumption combined driving (auto)</th>
<th>4.5* kg/100 km (gas) [approx 6.8 l/100 km petrol equivalent]</th>
<th>6.7* litres/100 km (petrol)</th>
</tr>
</thead>
</table>

| Emission standard | Euro 6 |

*Preliminary data*

**V60 Results**

- Gasoline: 240 g/km
- Port Injection (GDI): 200 g/km
- Diesel: 160 g/km
- Common Rail: 120 g/km

**CO2e Emissions g/km**

- CH4*34
- CO2

*Preliminary data*
Progression of Natural Gas Technologies in Light Duty Space

1. Gasoline NA PFI engines with NG PFI

2. Turbo Gasoline DI engines with NG PFI

3. Turbo Gasoline DI engines with NG DI

**Better.** Delphi, Conti and Bosch developing NG DI FIE. Exceeds gasoline performance & efficiency.

**Good.** Current OEM state-of-the-art. Only Volvo (Westport), VW and Mercedes in Europe. Matches gasoline performance*.

**Common.** Current/prior generation. Slightly degraded peak power & torque relative to gasoline.

* Gasoline co-fueling and other protection countermeasures required in NG mode.
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 Natural Gas Technologies in Light Duty Space

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**Good.** Current OEM state-of-the-art. Only Volvo (Westport), VW and Mercedes in Europe. Matches gasoline performance*.

**Better.** Delphi, Conti and Bosch developing NG DI FIE. Exceeds gasoline performance & efficiency.

**Best.** Outperforms gasoline and matches or exceeds diesel performance.

*Gasoline co-fueling and other protection countermeasures required in NG mode.
## Diesel-Derived Spark-Ignited Medium Duty NG Engines

<table>
<thead>
<tr>
<th>Year</th>
<th>Technology Description</th>
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</tr>
</thead>
<tbody>
<tr>
<td>1992</td>
<td>Lean Burn Technology</td>
<td>2004</td>
<td>Stoichiometric with Cooled EGR Technology</td>
<td>2007</td>
<td>High Efficiency SI (HESI) Technology</td>
</tr>
<tr>
<td></td>
<td>Cummins L10 G launched</td>
<td></td>
<td>1st demonstrated in 2004</td>
<td></td>
<td>1st demonstrated</td>
</tr>
<tr>
<td></td>
<td>1st CNG bus engine</td>
<td></td>
<td>1st launched - CWI ISL G - in 2007</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Lean Burn Technology
- Cummins L10G launched 1st CNG bus engine
- High excess air with turbocharging
- Much lower NOx & PM than diesel
- 25% lower peak torque than diesel

### Stoichiometric with Cooled EGR Technology
- Oxygen-free exhaust using cooled EGR → 3-way catalyst
- 15-25% lower peak torque than diesel

### High Efficiency SI (HESI) Technology
- Retains stoich + EGR combustion
- Removes constraint of common cylinder head with diesel engine
- Higher peak torque than diesel
- Enables downsizing
  - Tumble air motion
  - High turbulent kinetic energy (TKE) at point of ignition
High Efficiency SI (HESI) Engine Cylinder Head Features

The HESI cylinder head is a fundamental enabling technology that determines design of other engine components.

When integrated with a pre-existing diesel engine bottom end (engine block, crankshaft, main bearings, etc.), it enables high efficiency, high output Otto-cycle combustion.
Heat Release Rate Comparison

- Tumble combustion system provides high turbulent kinetic energy at point of ignition
  - Intensifies mixing, promoting efficient combustion
- Increased flame propagation speed, causing rapid heat release rate after ignition
- Lower exhaust temperature but higher cylinder pressure
- Strong bottom-end needed to maximise the benefit of the approach

1 litre/ cylinder
Full Load 1500 rev/min

Heat release rate [kW]

Crank angle (degree)
Estimated CO2 Benefit versus 2027 Requirement
Heavy Duty Pickup

» Analytical comparison of options based on experience, GT-Power analysis and comparison with published literature [1,2].

» Un-throttled NG engine not really practical in this segment due to cost, aftertreatment and packaging reasons.
  ▪ Methane emissions may also offset a significant proportion of the CO2 reduction depending upon combustion strategy

» HESI with VVT (MHD solution) provides a significant CO2 reduction but only half of the fuel carbon intensity benefit is captured

» HESI with cylinder deactivation could provide enough benefit to meet the reductions called for by 2027

1: DOT HS 812 194, February 2016, Commercial Medium- and Heavy-Duty Truck Fuel Efficiency Technology Study – Report #2
Summary – High Efficiency SI

» High efficiency SI can make an impact in Class 2b/3 by offering capability equal to diesel with rapid payback (zero to small premium over diesel)

» Dedicated natural gas cylinder head approach for diesel bottom end provides significant benefits in performance, efficiency and robustness

» SI technology is progressing but there is still a lot more to come
  - SI DI CNG in light duty around 2020
  - Optimised SI DI (step 4) in medium duty also around 2020
  - Combined technology package in HD pick-up for 2021?
The Challenge for Class 8 Trucks

- Over 20% reduction in CO2 required for Class 8 tractors over the next 10 years
- Powertrain and vehicle technology combinations are required to meet this target
- Efficient natural gas technologies stand to make a significant contribution

AVL viewpoint
Westport HPDI for Class 8 Trucks

» HPDI Principles and Rationale
» Fuel System Overview
  ▪ HPDI Injectors
  ▪ Fuel Conditioning Modules
  ▪ LNG Tank and Pump
» Performance and Emissions
» Outlook and GHG 2 impact
HPDI Technology Principles

» Reproduces Diesel Cycle but with mostly natural gas.

» Diesel base engine configuration
  ▪ Same power cylinder architecture, including compression ratio
  ▪ Same air handling system
  ▪ Same control approach

» Fuel injected at high pressure at end of compression stroke
  ▪ Diesel Pilot – For Ignition
  ▪ Natural Gas
  ▪ Generally variable rail pressure up to 300 bar for both fuels

» Low diesel usage
  ▪ 5% to 10% diesel over vehicle operating cycle
HPDI Technology Benefits

» Provides the same power and torque capability as the parent diesel engine
» Provides same drivability (transient response)
» Provides same engine compression braking
» Maintains high efficiency of diesel cycle - minimizes CO2e emissions

» Engine Development perspective
  - Minimizes changes to the base diesel engine
  - Aligned with diesel emissions control equipment and strategies
  - Similar exhaust temperatures
Fuel System Overview
Technology Progression: HPDI 1.0 to HPDI 2.0

» 1300 HPDI 1.0 trucks deployed between 2007 and 2013
  ▪ First generation fuel system installed by Westport on purchased Cummins 15L ISX engines and standard after-treatment

» Lessons learned
  ▪ Drivability and Performance generally well liked
  ▪ Product not robust in all situations
  ▪ Cost too high
  ▪ Incompatible with the new generation of HD engines coming to the market – 2nd generation required

» HPDI 2.0 designed to overcome limitations of HPDI 1.0

» Components designed & developed in conjunction with industry-leading component manufacturers, including Delphi Diesel Systems

» HPDI 2.0 injector up to 500 bar pressure capable
» Initial implementation 300 bar
Technology Progression: Fuel Storage and Supply System

» Completely re-designed
» Cost reduced, quality improved, easier integration
» Integrated LNG Pump
» High & low pressure variants
» Enables cold LNG for increased range and longer hold times

Integrating Gas Module

High Pressure LNG Pump
HPDI 2.0 Results

HPDI 2.0 Fuel System was adapted to two European heavy-duty in-line 6 cylinder engines with peak ratings above 360kW.

The two engines rely on a combination of combustion phasing, EGR and EATS to meet emissions requirement.
- EATS = SCR, DOC & DPF

Calibrated using standard design of experiment methods to optimize:
- Injection timing (and pilot to gas delay)
- Fuel pressure
- EGR and air handling
  - EGR rates are generally reduced from base diesel engine

Operate within the base engine mechanical and thermal limits.

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<table>
<thead>
<tr>
<th>Euro VI Type 1-A dual fuel limits</th>
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<tbody>
<tr>
<td>NOx</td>
</tr>
<tr>
<td>PM</td>
</tr>
<tr>
<td>CO</td>
</tr>
<tr>
<td>nmHC</td>
</tr>
<tr>
<td>CH4</td>
</tr>
<tr>
<td>NH3*</td>
</tr>
</tbody>
</table>

Type 1-A dual fuel definition
1. Engine must idle using both diesel and natural gas.
2. The gas energy ratio (GER) must be greater than 90% as measured over a warm WHTC.
3. Emissions testing only required over combined hot-cold WHTC. No WHSC testing required.

*(for systems with SCR)
Gas Energy Ratio

» Gas Energy Ratio (GER) is defined as natural gas energy / total fuel energy

» Driven principally by the minimum diesel injection quantity that produces stable combustion
Combustion

Engine "A"
- 75% load
- 25% load

Engine "B"
- 75% load
- 25% load

Pressure (% of max)

AHRR (kJ/m³/oCA)

Crank Angle (oCA)

pilot
main gas
HPDI t90 response, relative to base diesel, as a function of sweep

(t90 - time from 0% to 90% of rated torque at each speed)
## Overall Performance Measures

<table>
<thead>
<tr>
<th>Measure</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Efficiency (%), including hydraulic pump parasitic load*</td>
<td>up to 46%</td>
</tr>
<tr>
<td>Road duty cycle BSFC relative to diesel. HPDI includes hydraulic pump parasitic*</td>
<td>1.01-1.03</td>
</tr>
<tr>
<td>Tailpipe GHG over various transient cycles, relative to diesel</td>
<td>0.80-0.82</td>
</tr>
<tr>
<td>Road duty cycle Gas Energy Ratio (GER)</td>
<td>0.94-0.95</td>
</tr>
<tr>
<td>World Harmonized Test Cycle GER</td>
<td>0.91-0.93</td>
</tr>
<tr>
<td>Emissions</td>
<td><strong>NOx, CH4, nmHC, CO and PM emissions demonstrated to meet Euro VI requirements.</strong></td>
</tr>
</tbody>
</table>

*Average LNG pump parasitic load over certification or typical operating cycles corresponds to a fuel consumption increase of approximately 2%
GHG Compliance Impact of HPDI 2.0

» Phase II rule requires CO₂ reduction of approximately 5% for a HD engine by 2027 compared to 2017 baseline

» HPDI offers potential for ~20% CO₂e reduction on a HD engine

» Without further engine modifications, this provides potential transfer of ~15% CO₂ saving to a HD tractor
  - Could lower compliance cost by avoiding more expensive CO₂ reduction options such as Waste Heat Recovery
  - Or it could be used to generate credits

Assumptions:
- Fuel energy consumption 2% greater than base diesel
- Fuel consumption: 8% diesel, 92% NG by energy
- 0.2% CH4 slip CH4 GWP of 34
Effect of Increasing Gas Pressure
(McTaggart-Cowan et al., SAE 2015-01-0865)
Summary – HPDI 2.0 for Class 8 Trucks

» HPDI 2.0 is designed for high BMEP (~24 bar), high efficiency (~45%), Class 8 (or equivalent) on-road engines with displacement of 10 to 15L
» Performance, efficiency and emissions and diesel-like transient response confirmed on two separate EU VI engine platforms
» Methane emissions are controlled to extremely low levels in-cylinder (<0.2% slip)
» GHG savings in the range of 20% are possible
» There is future potential for enhancements (e.g. increased injection pressures for higher efficiency).
QUESTIONS?

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