State of the Art and Future Developments In Natural Gas Engine Technologies

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Introduction

- Content and performance of today's natural gas products
  - Plus technology
  - Emissions results
- Near term developments
- 2007/10 emission solutions
  - Options for natural gas engines
  - Early-stage results

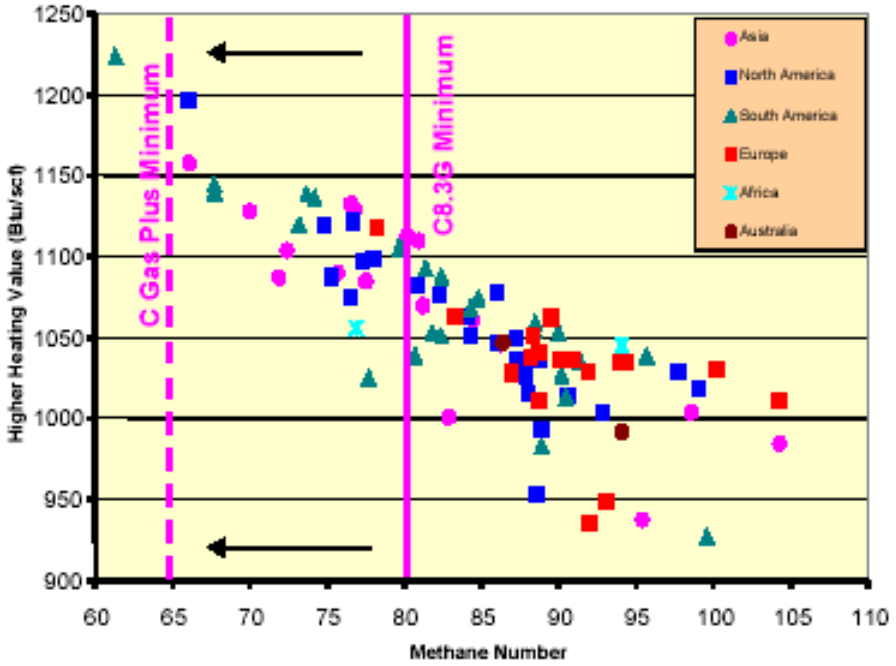
Plus Technology Engines

- Available in North American and European markets
  - B-Series (5.9liter) and C-Series (8.3liter) platforms
- Highly capable electronic controls
  - Elimination of separate electronic governor control module
  - Drive-by-wire
  - Knock sensing and control
  - Wide fuel range compatibility
    - As low as 65 methane number
- Oxidation catalyst as standard

C Gas Plus Engine

- 280hp / 850ft-lbs
- Certified at 1.5g/bhp-hr NOx, 0.01g/bhp-hr PM
- Launched July 2001
- >1500 units in the field
  - Mostly North American transit fleets
- Full description in SAE 2002-01-2737
- Vehicle based emissions tests to date
  - CARB transit bus study (Ayala et al.)
  - WVU, NREL transit bus (WMATA), HD Truck (Viking)

Fuel Compatibility



- Gas composition has geographical and seasonal variation
- Methane number is an indication of fuels propensity to knock
- Composition also influences metered energy flow
- Electronic controls minimize impact of fuel quality on performance and emissions

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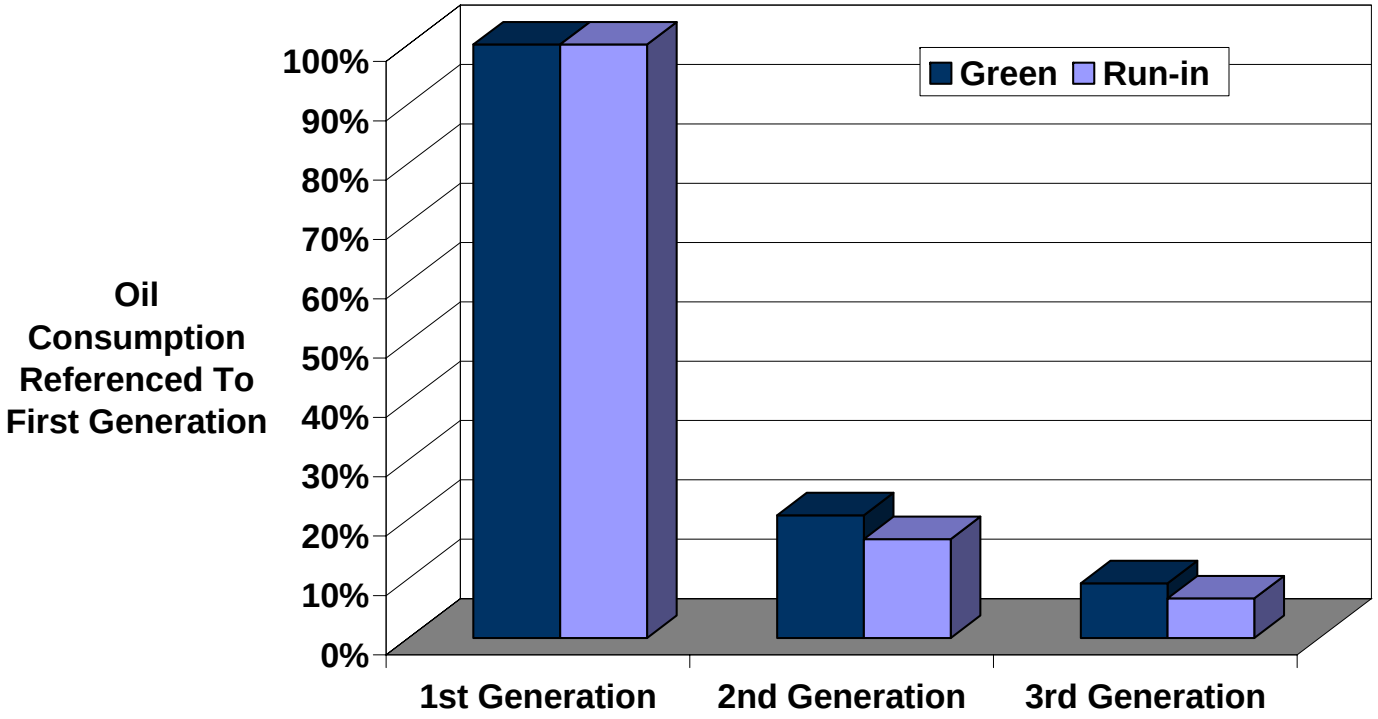
Use of Oxidation Catalysts With Plus Technology Engines

- Natural gas is inherently ultra-low Sulfur therefore very active catalysts can be used
- An oxidation catalyst is standard component of all Plus technology lean burn engines
  - PM, NMHC, aldehydes, CO control
  - Significant reduction in ultrafine particles (normally assumed to be mostly VOCs[1])

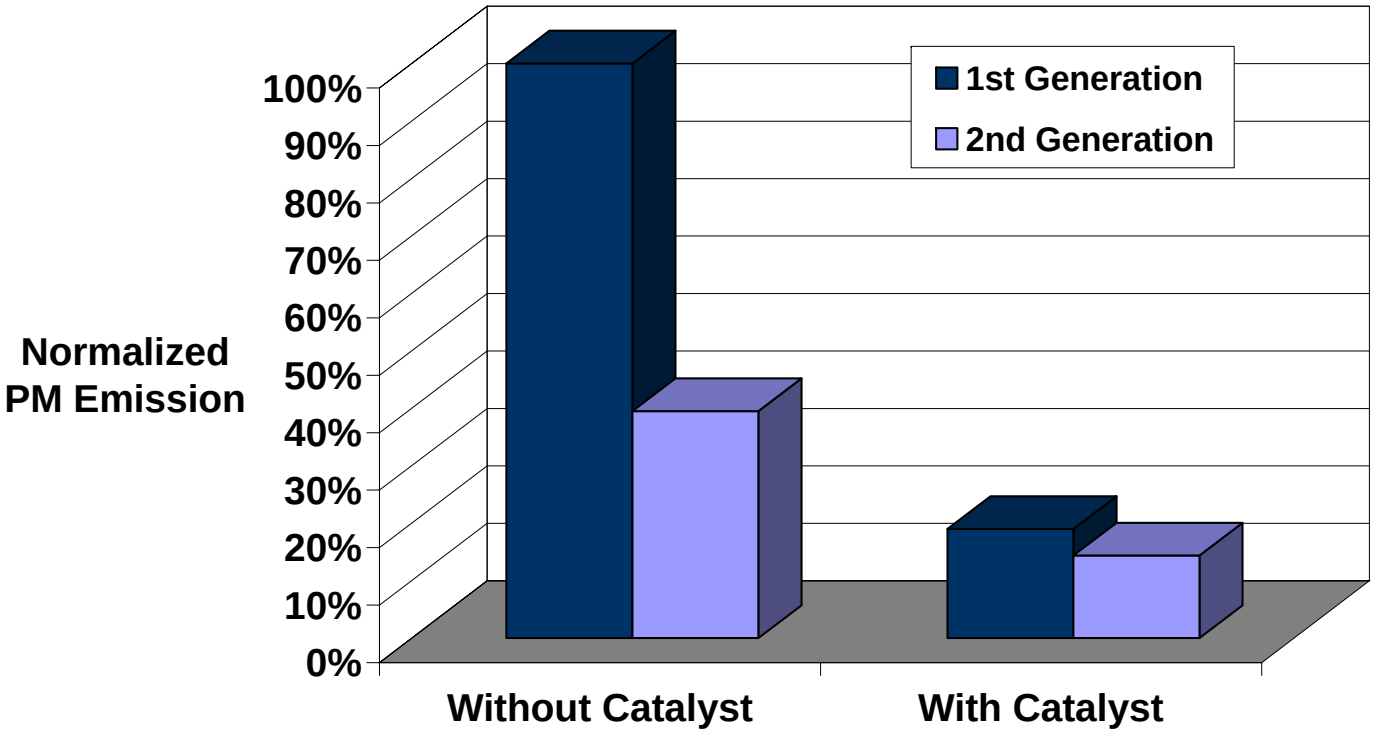
1. Andersson, J & Wedekind, B, 2001. DETR/SMMT/CONCAWE Particulate Research Programme, Summary Report. Ricardo Report DP01/0515

Evolution of Oil Control



- Oil control particularly important for PM emission reduction
- Oil consumption at idle is 90% lower in the 3rd generation when compared to the 1st

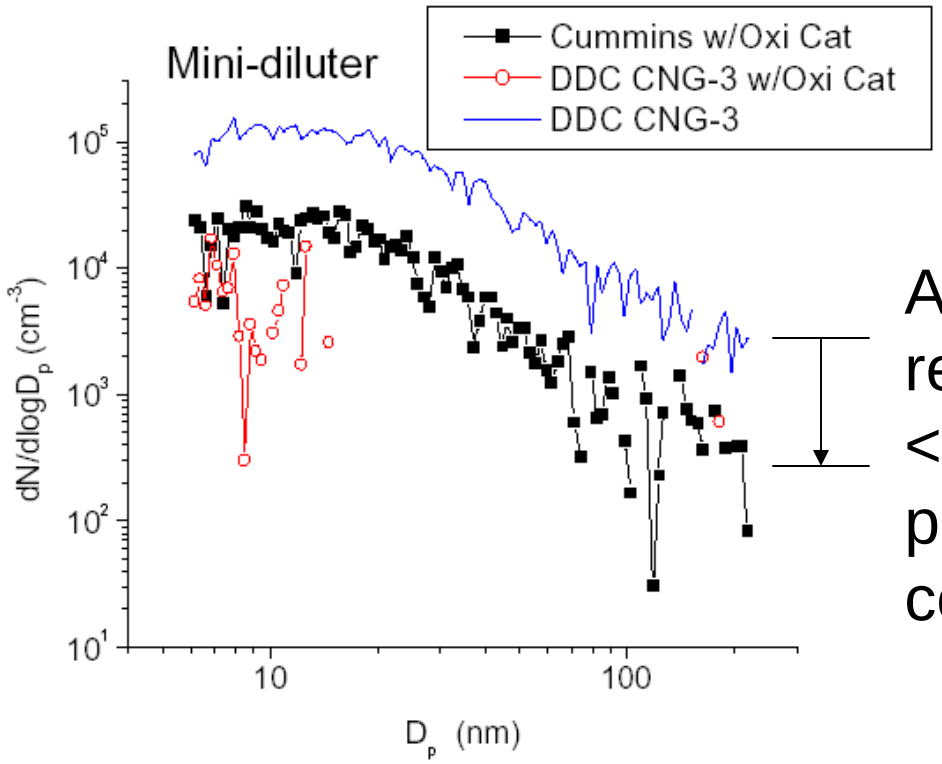
Oil Control and PM Emissions



- Previous generation of same engine type without catalyst has almost x10 PM of later generation
- PM conversion efficiency of oxi-cat lower with later generation
  - Indicates lower SOF in PM following oil control improvements

Oxidation Catalyst Effective at Ultrafine Reduction

CNG buses: Steady-State 55 MPH



Approx 90% reduction in <100nm particle concentration

Ref: Holmen B, Ayala, A. Oxidation Catalyst Effects on Natural Gas Transit Bus Ultrafine Particle Emissions. 6th International ETH Conference on Nanoparticle Measurements August 19-21, 2002, Zurich.

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C Gas Plus Engine Certification Emission Results

Urban bus certification results (g/bhp-hr)

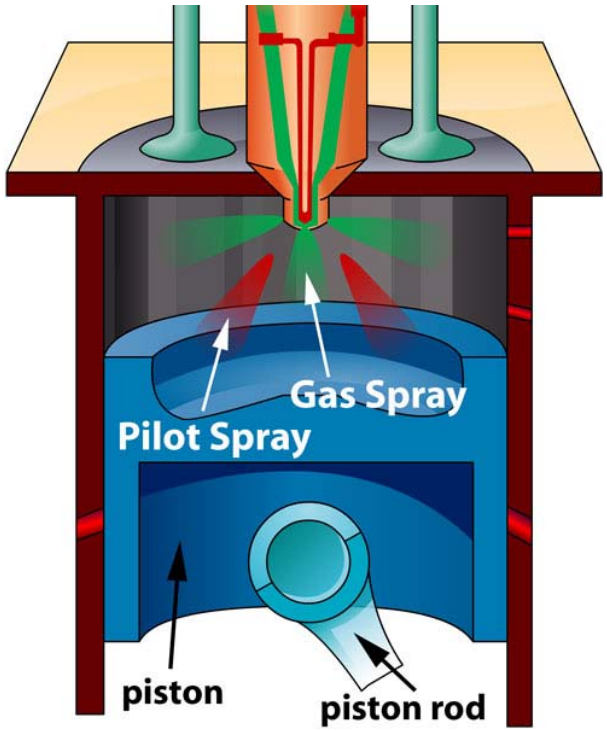
	NOx	NMHC	CO	PM	HCHO
Transient Test	1.5	0.2	2	0.01	0.019
SET Test	1.5	0	1.3	0.01	N/A

Ref: SAE 2002-01-2737

Near Term Developments

- Application of Plus technology to ISL platform (L Gas Plus)
  - 8.9 liter, 320hp, 950ft-lbs
- Commercialization of Westport-Cycle™ (HPDI) technology on heavy duty platforms
  - High BMEP, high efficiency combustion approach
    - translates into Green House Gas benefits
  - Initial application ISX G
  - Utilizes cooled EGR system of ISX ’02
- Investigation of hydrogen / natural gas blends

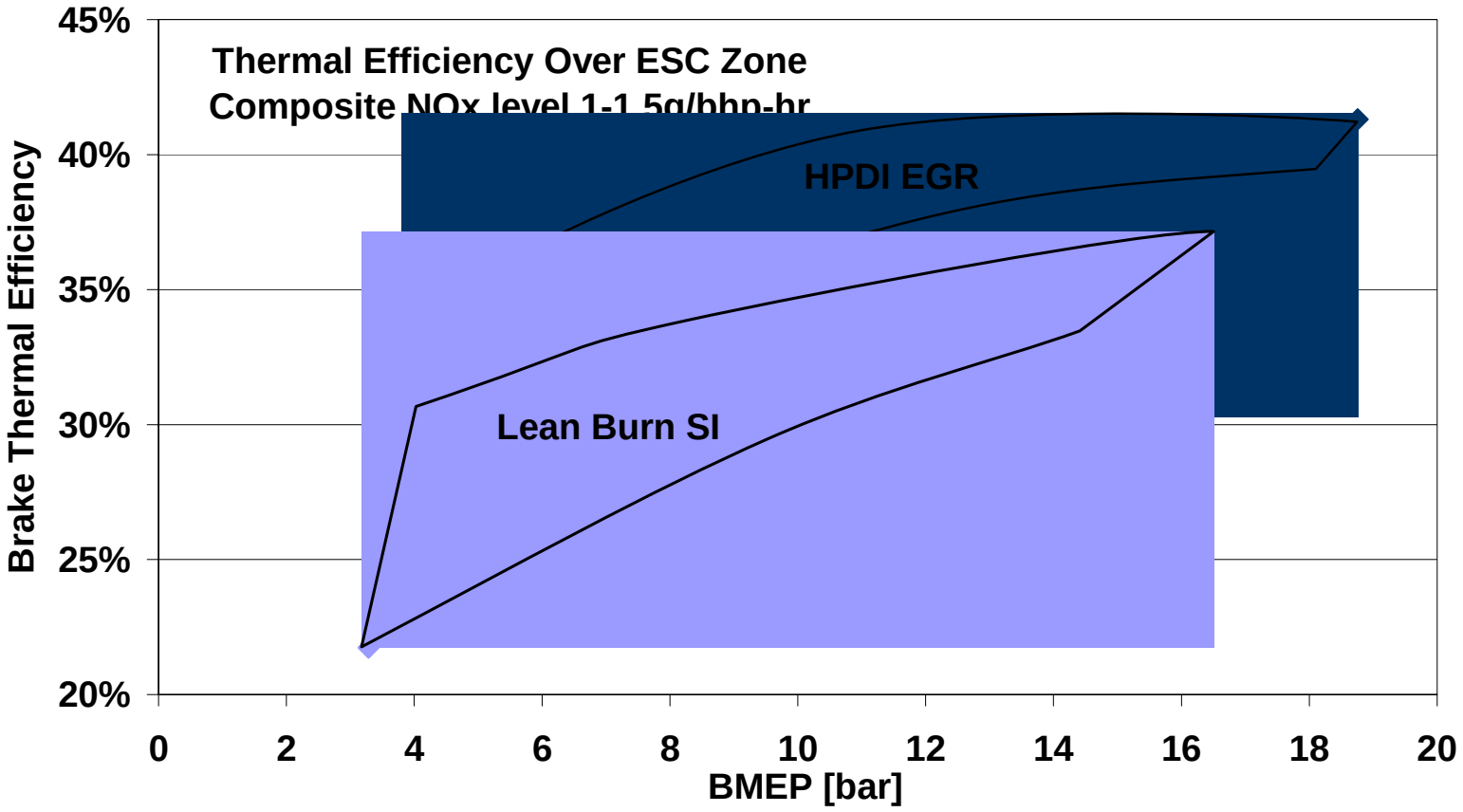
Pilot Ignited HPDI Process



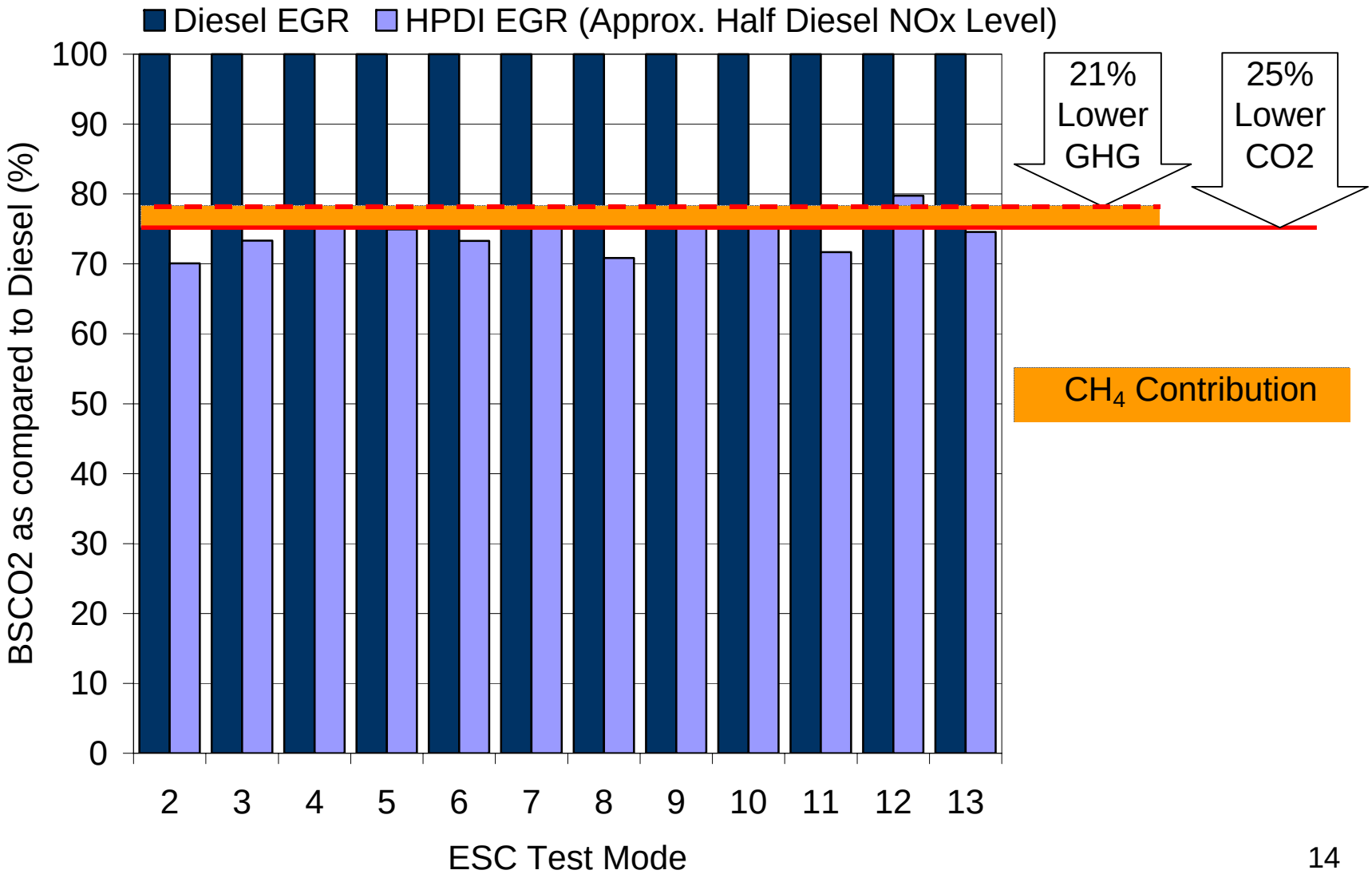
- Retains Diesel cycle: high low-speed torque, efficiency
- Small quantity of pilot diesel injected before natural gas to provide ignition
- Natural gas injected at high pressure during combustion phase
- For automotive applications, high pressure natural gas is derived from pressurized LNG

Approx. emissions reduction ISX G vs. ISX '02	NOx	PM	GHG
	-50%	-70%	-20%

Efficiency of HPDI Compared To Lean Burn SI

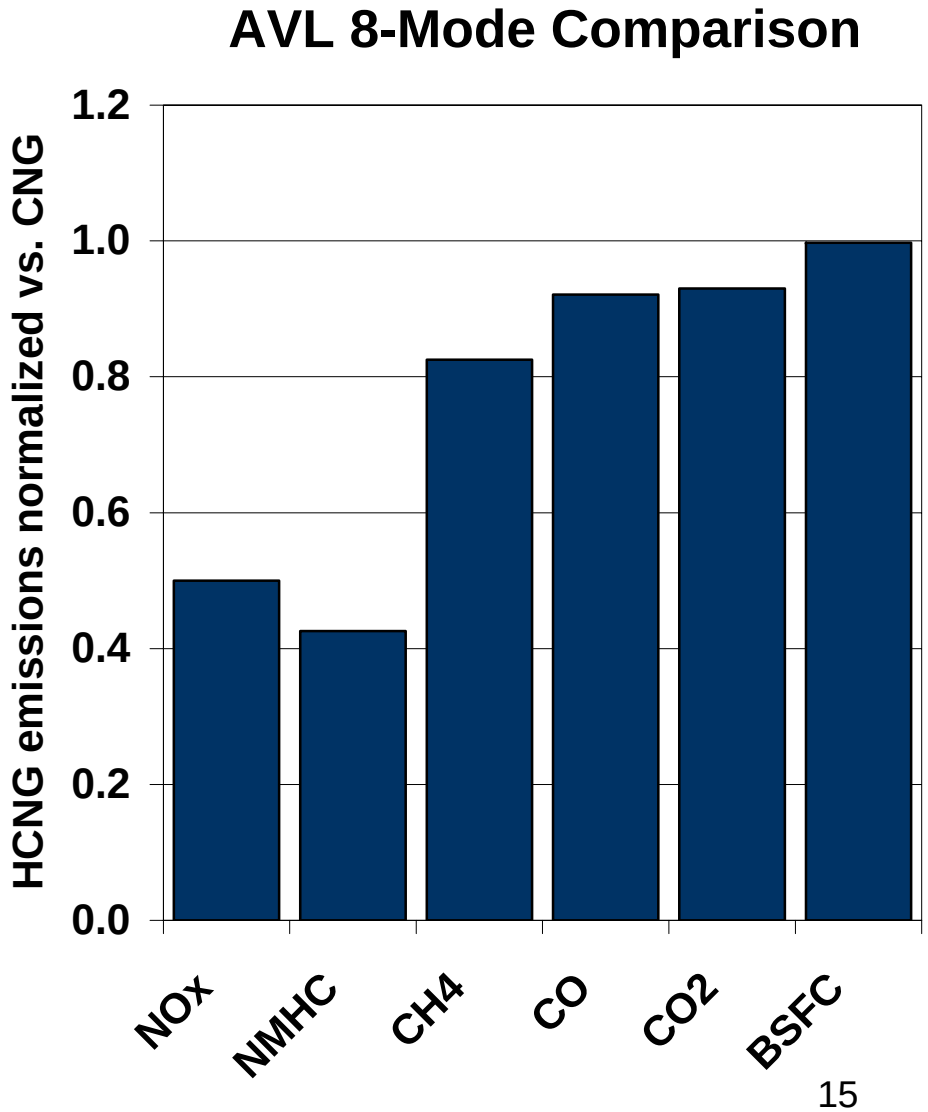


GHG Benefits of HPDI



Hydrogen / Natural Gas Blends

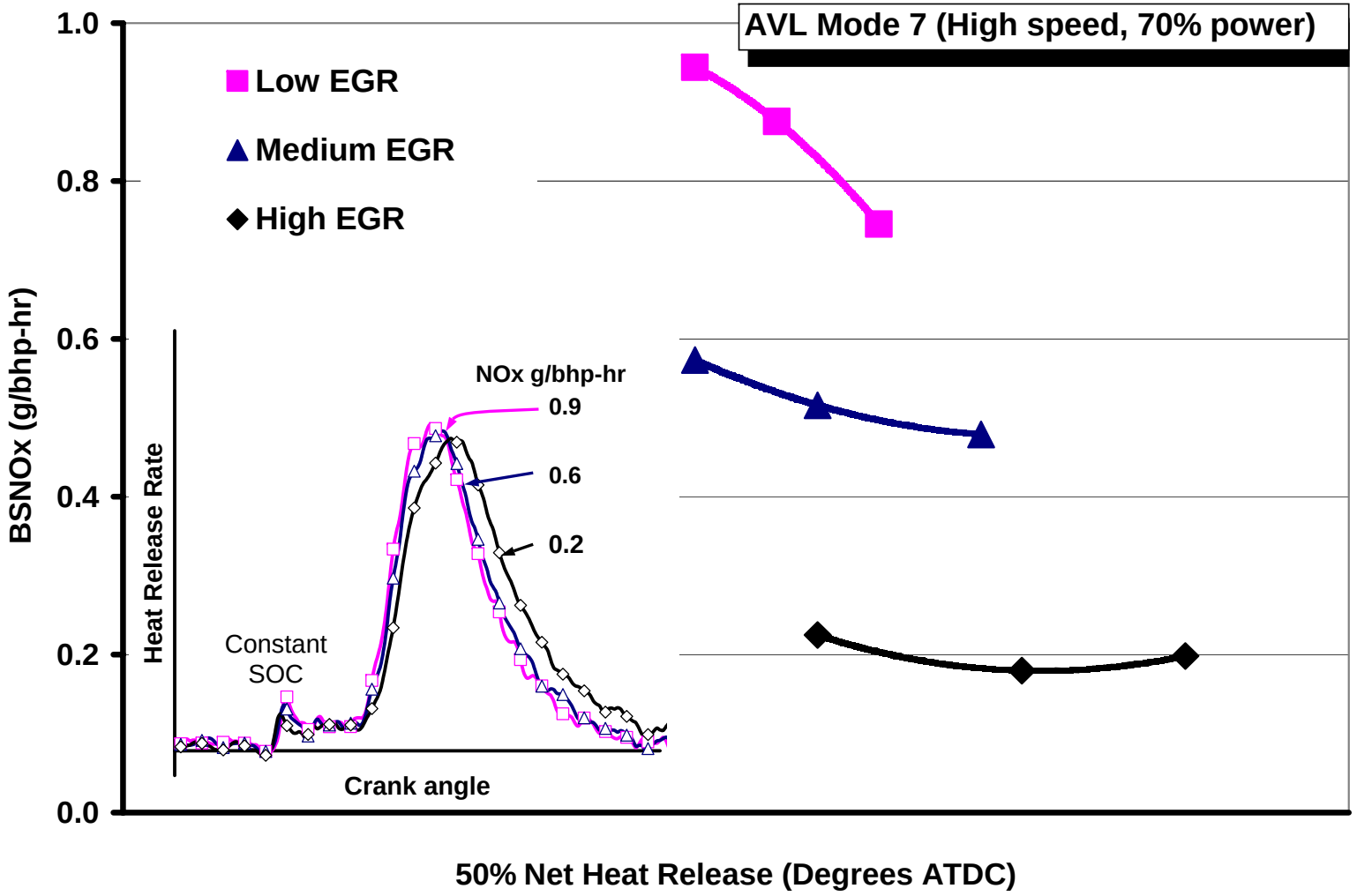
- Natural gas is an ideal carrier for small amounts of hydrogen
- Higher flame speed leads to lower NOx for same efficiency (leaner operation)
- Under demonstration using B Gas Plus platform at SunLine Transit
  - 20mol% H2/CNG blend



2007/10 Technology Developments

- Focus will remain on highly diluted combustion
  - Homogenous and stratified modes
- Level of in-cylinder versus post-combustion NOx control remains under review
  - Lean NOx aftertreatment can be used (often with fewer complications due to lower emission feed-gas)
  - Positive signs for more cost effective approaches
- Continued use of oxidation catalysts for PM control
- Constant or improving efficiency expected as 2010 approaches
- Strong program supported by NREL, SCAQMD, CEC, Technology Partnerships Canada, NRCan

Ultra-Low NOx With Cooled EGR



- Combustion tolerant to high levels of EGR providing very low NOx potential

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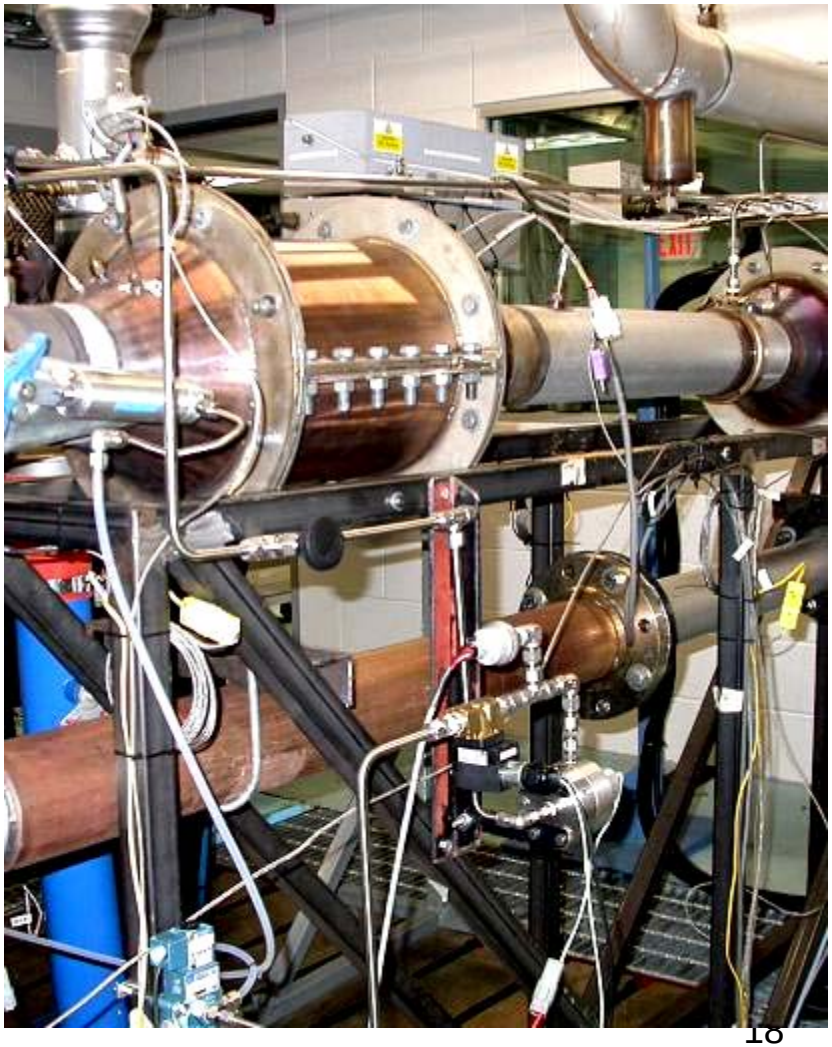
Natural Gas with NOx Storage And Reduction

- ~10ppm fuel Sulfur with CNG
- ~1ppm fuel Sulfur with HPDI LNG/ULSD
- Possible to achieve regeneration & desulphation with natural gas reductant
- Single bed system
  - 90% conversion efficiency with 2.5% fuel penalty (de-greened condition)
- High deterioration factors at present



Spark Ignition with Cooled EGR

- SI engines can take advantage of diesel engine cooled EGR technology
- Numerous examples of flame propagation engines operating with cooled EGR
  - Lean-EGR can improve in-cylinder NOx control (stability/HC emissions concerns)
  - Stoich-EGR-TWC offers low cost aftertreatment approach but is in infancy for HD automotive applications
- SI + cooled EGR technology development ongoing under the NGNGV program.

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Natural Gas Engine Outlook

- Product capability has grown with the integration of latest technologies
- Very low emissions are available in commercial products today
- Technical evolution will continue through the decade
- Multiple technologies and development paths exist to 2010
  - Flexibility and new technologies offer the potential for low emissions and efficiency improvement
- CWI expect to offer commercial products that significantly surpass mandatory emission standards through to 2010