Ricardo's ACTION Strategy: An Enabling Light Duty Diesel Technology for the US Market

11th Diesel Engine Emissions Reduction Conference

21st – 25th August 2005

Palmer House Hilton, Chicago

Adrian Greaney – Chief Program Engineer, Light Duty Diesel, Ricardo
adrian.greaney@ricardo.com

Our industry has already made remarkable progress in light duty diesel technology…..

Last significant US consumer experience in early/mid 1980's

180%
160%
140%
120%
100%
80%
60%
40%
20%
0%

AVG. SPECIFIC TORQUE

AVG. SPECIFIC POWER

EU FLEET AVG. CO_2

PM EMISSIONS

NOx EMISSIONS

EU2 EU3 EU4

1996 1998 2000 2002 2004 2006 2008 2010

…..and developments continue to show significant potential for future US and global diesel products…….

Contents

- Critical challenges in developing light duty diesel solutions for the US
- Ricardo's approach to meeting the US diesel challenge
- Status update on minimum engine-out NOx development
- Summary and conclusions

Contents

- Critical challenges in developing light duty diesel solutions for the US
- Ricardo's approach to meeting the US diesel challenge
- Status update on minimum engine-out NOx development
- Summary and conclusions

There are many challenges in developing light duty diesel solutions for the US market

Technology Strategy

- Lowest system cost
- Engine technology selection
- Aftertreatment technology selection
- Control approach & OBD
- Emissions variability & durability
- Retain diesel fuel economy benefit
- Deliver performance & refinement
- Commonality with Euro technology
- Robustness to fuel quality

Market/Product Strategy

- Diesel vehicle selection
- US specific or shared EU platforms
- Alignment to gasoline products
- Alignment to hybrid products
- Pricing strategy
- 45 States (Bin8) or 50 States (Bin5)
- CAFE strategy
- Market acceptance

ACHIEVE VIABLE BUSINESS CASE

Contents

- Critical challenges in developing light duty diesel solutions for the US
- Ricardo's approach to meeting the US diesel challenge
- Status update on minimum engine-out NOx development
- Summary and conclusions

Achieving a viable business case remains the most significant challenge to Light Duty Diesel growth in the US market, and is highly dependent on the selected emissions technology strategy

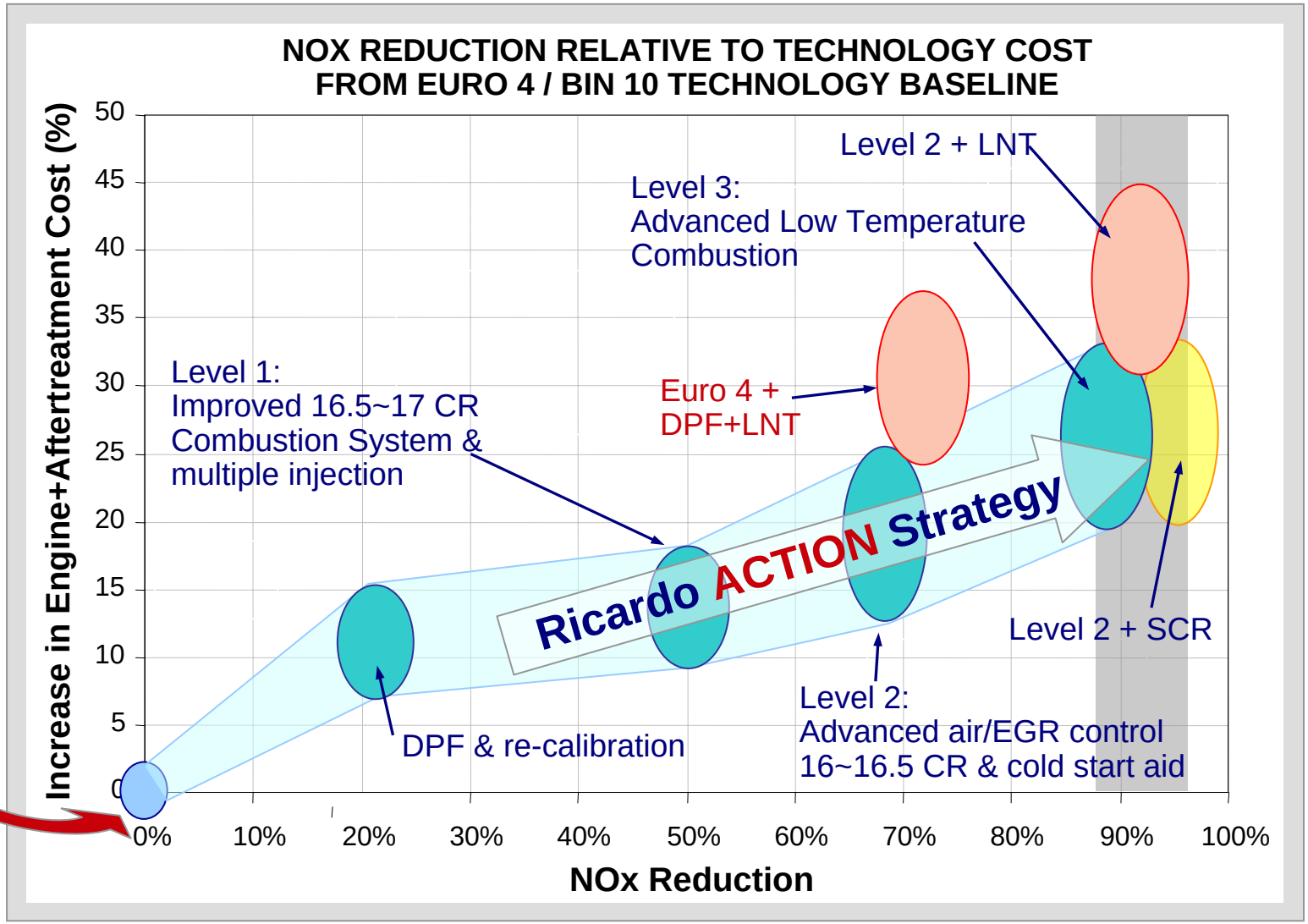
BASELINE

4-5L V8 HSDI

$4k - $4.5k variable cost

~100k units per year

Euro 4 / Bin10 technology with oxidation catalyst only

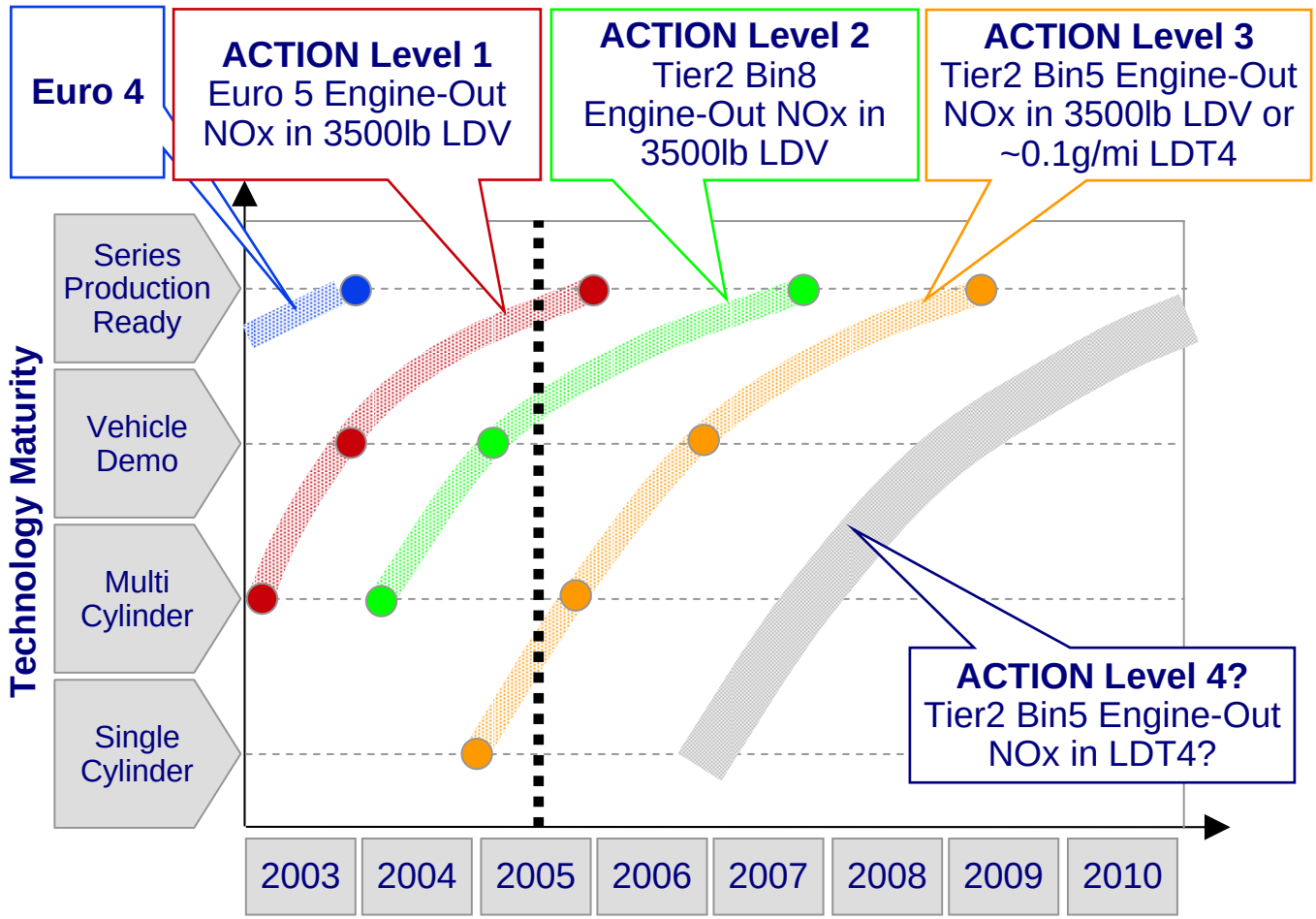


ACTION is a diesel engine technology strategy to provide lowest cost robust emissions solutions through engine-out NOx reduction

Advanced Combustion Technology for Improved engine-Out NOx

Targets support Euro 5 and US Tier 2 Bin 5 Requirements

Approach consists of a progressive roadmap of technology development



- REDUCED ENGINE-OUT NOx
- IMPROVED PERFORMANCE
- RETAIN FUEL ECONOMY BENEFIT

Two approaches exist to lowering engine NOx and soot levels but both are often called "HCCI"

Low NOx and soot diesel combustion strategies

Homogeneous Charge Compression Ignition (HCCI)

Homogeneous. low temperature combustion achieved by early injection

- Injection timings before -30 °CA ATDC
- Low [O_2] to retard and control RoHR
- Multiple injections
- High levels of swirl

- Ultra-low NOx and soot emissions
- Large increase in HC and CO emissions
- Maximum load limited
- Major control challenge due to mode switching
- Combustion phasing challenge

Long-term option, but with many practical problems to solve?

Partial HCCI or Highly Premixed Cool Combustion (HPCC)

Highly pre-mixed combustion achieved by injecting fuel during the ignition delay period

- Injection timings near TDC
- Low [O_2] to control RoHR
- High rail pressures
- High levels of swirl

- Very low NOx and soot emissions
- Moderate increases in HC and CO emissions
- Increase in fuel consumption if combustion too late
- Application over wider operating zone
- More practical control

Practical approach for near-term introduction

Progressive technology developments are enabling highly pre-mixed cool combustion (HPCC) to achieve T2 Bin 5 engine-out

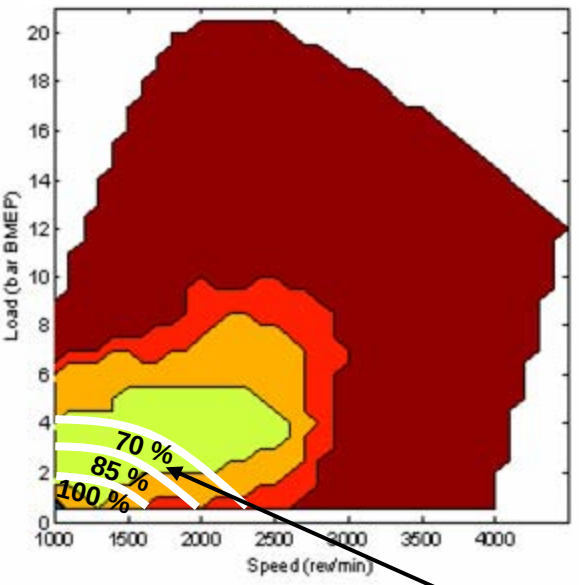
Euro 4
Baseline
(Engine-Out NOx)

LEVEL 2
T2 Bin 8
(Engine-Out NOx)

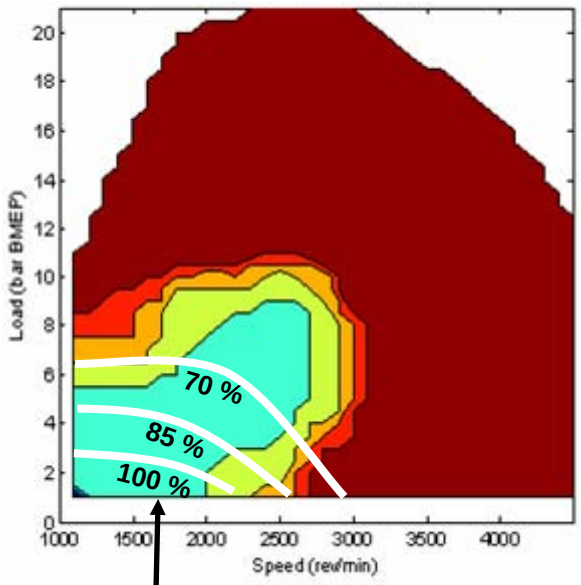
LEVEL 3
T2 Bin 5
(Engine-Out NOx)

ACTION ROADMAP
(Advanced Combustion Technology to Improve engine-Out NOx)

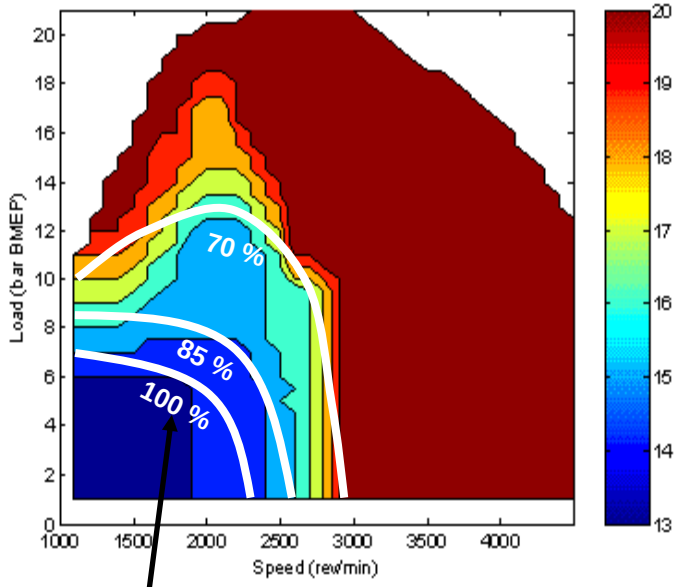
Euro 4 – O_2 Concentration Map



Level 2 – O_2 Concentration Map



Level 3 – O_2 Concentration Map



Numbers indicate percentage of fuel injected before start of combustion of the main injection

The Ricardo ACTION engine technology roadmap uses an incremental approach to meet the future diesel challenges

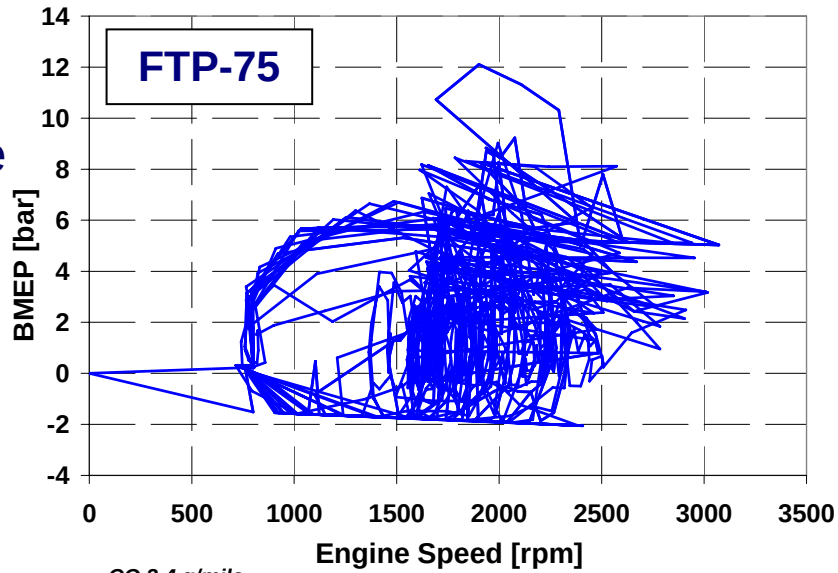
LEVEL 1 (T2 Bin 9 LDT, Euro 5 without NOx A/T)	LEVEL 2 (T2 Bin 8 LDT without NOx A/T)	LEVEL 3 (T2 Bin 5 LDV, Euro 6? without NOx A/T)	LEVEL 4 (TBC) (T2 Bin 5 LDT? without NOx A/T)
Air System Developments			
❑ Variable swirl ❑ EGR cooler+bypass ❑ 1 Stage VGT	❑ Enhanced EGR cooling & temperature control	❑ Staged boosting ❑ Advanced cooling strategies ❑ LP EGR (app.specific)	❑ Variable Valve Actuation
Combustion System Developments			
❑ Reduced CR (~17:1) ❑ 7 hole nozzles	❑ Reduced CR (~16.5:1) ❑ +8 hole nozzles ❑ Cold start enablers	❑ Reduced CR (~16:1) ❑ Highly Pre-mixed Combustion	❑ Variable nozzle technology
Increased multiple injection capability			
Increased fuel injection performance			
Closed Loop Control Development			
❑ Lambda sensor	❑ NOx sensor	❑ Combustion Feedback Control (CPEMS)	❑ In-Cycle Model-Based Control (ARTEMIS)
2005	2007/8	2010	2012+

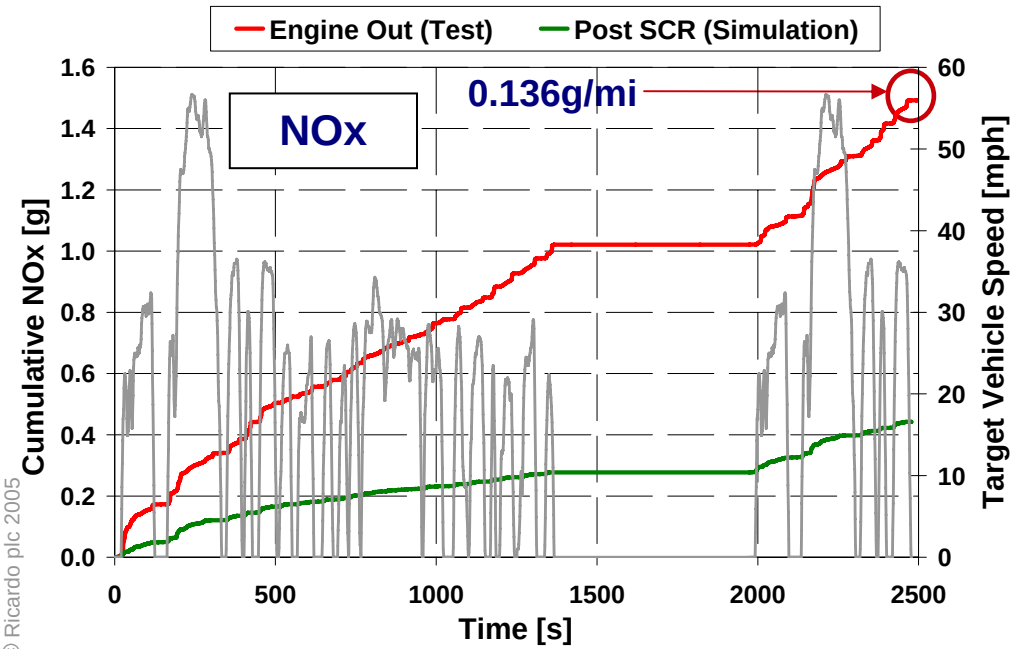
Contents

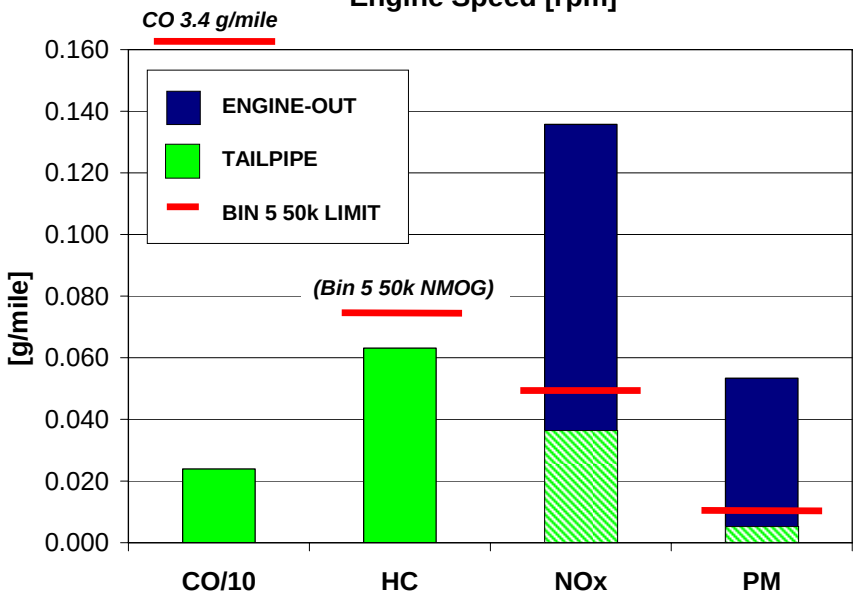
- Critical challenges in developing light duty diesel solutions for the US
- Ricardo's approach to meeting the US diesel challenge
- Status update on minimum engine-out NOx development
- Summary and conclusions

Preliminary assessment of Euro 5 vehicle on US cycles shows Bin 5 feasibility with ~60% aftertreatment deNOx requirement

- ~2L 3500lb ITW vehicle
- 75hp/liter specific rating
- ACTION Level 2 hardware with single stage VGT & enhanced EGR cooler with bypass
- No US specific hardware optimization
- Minimal calibration development
- Excludes Bin 5 combustion & air/EGR system developments



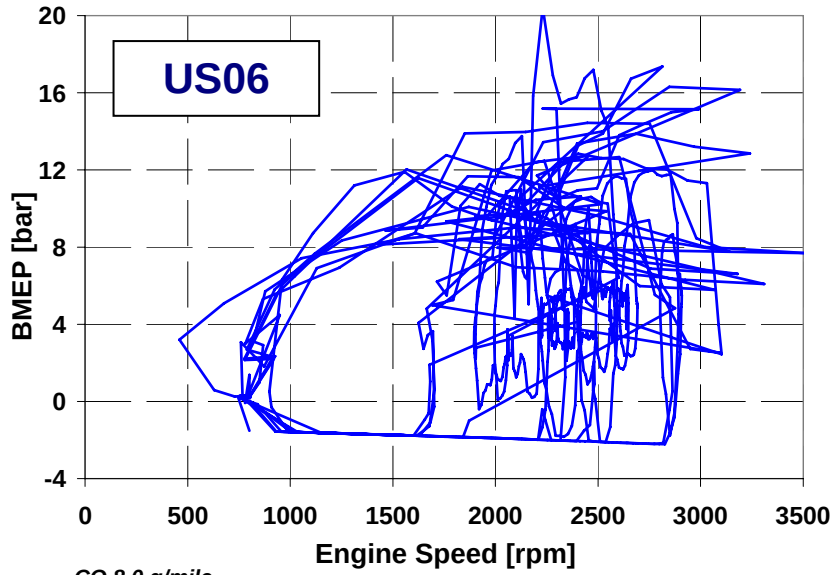


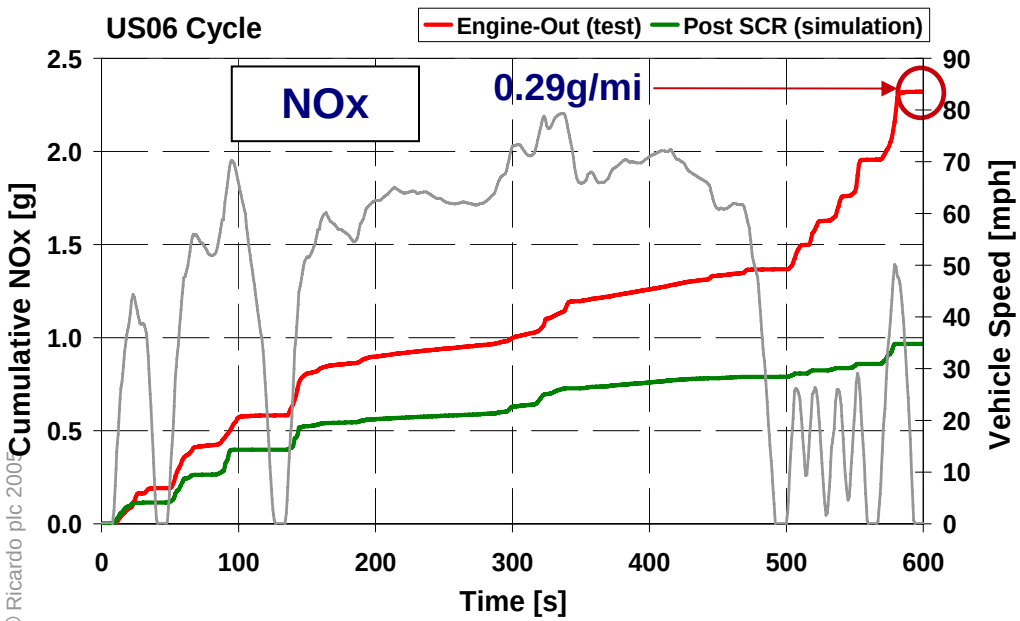


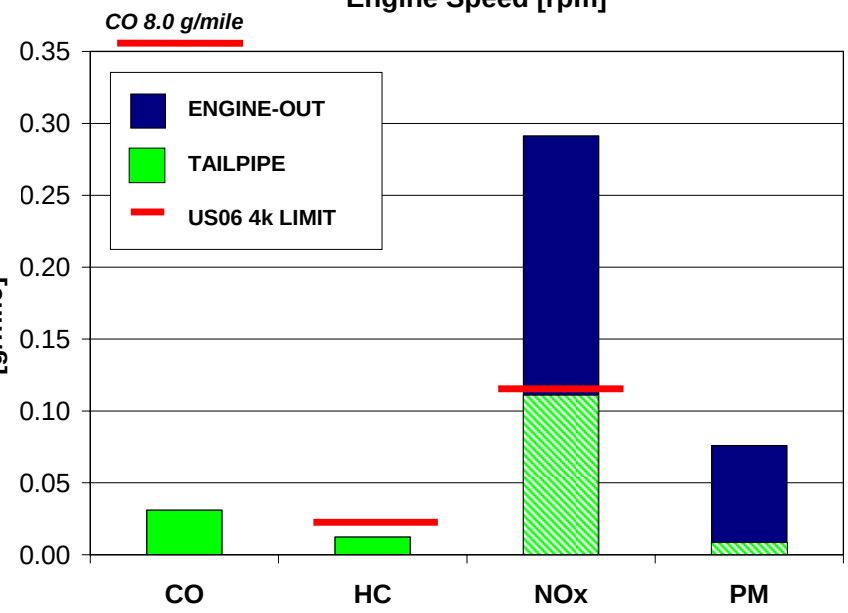
DEER 2005

Preliminary assessment of Euro 5 vehicle on US cycles shows Bin 5 feasibility with ~60% aftertreatment deNOx requirement

- US06 load increases to 20 bar BMEP
- 4k Tier 2 NOx feasible with ~60% aftertreatment NOx reduction
- Potential for further improvements with re-optimization of combustion & air/EGR system for higher loads
- FTP-75 fuel economy of 40.2mpg
- US06 fuel economy of 43.2mpg





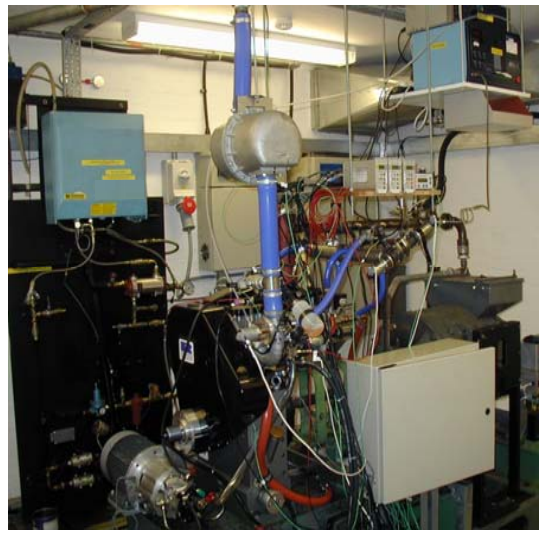


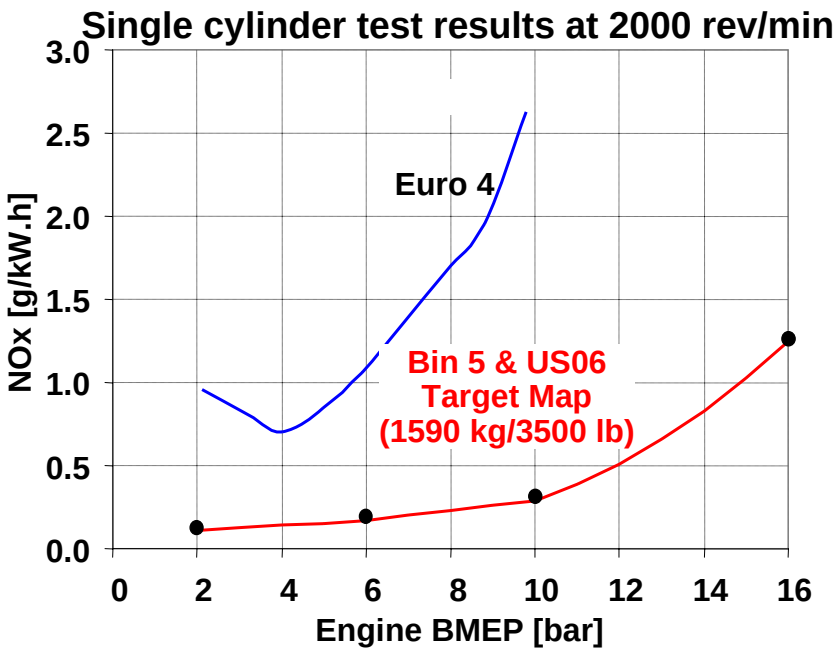
DEER 2005

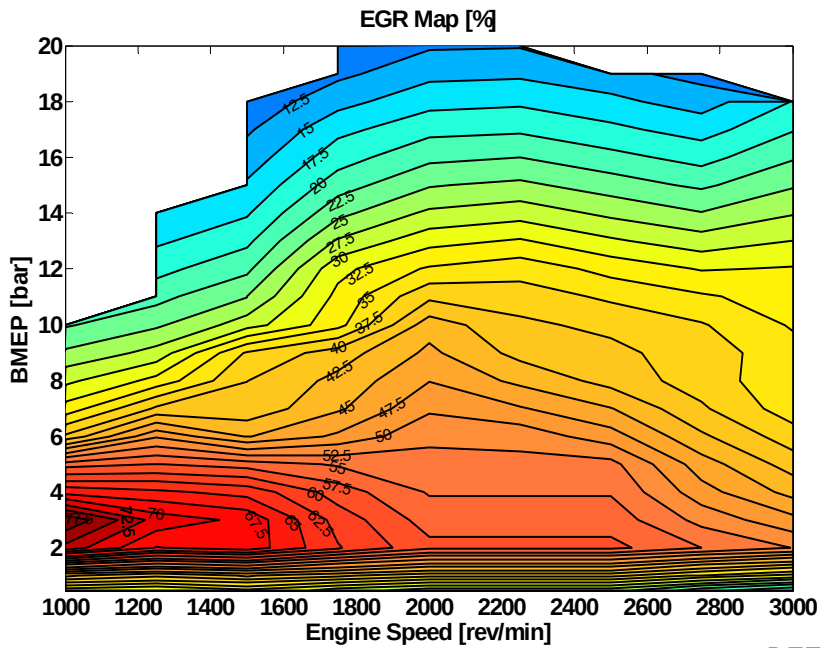
Single cylinder research tool has been used to investigate combustion fundamentals & define requirements for Tier2 Bin5

Research Status

- New single cylinder and optical engines established
- Strategy for ultra low NOx confirmed
- Air/EGR requirements for Bin 5 and US06 defined
- Combustion system hardware direction defined
- CFD design tools under development
- Bin 5 emissions potential demonstrated
- Next generation fuel system technology not yet exploited

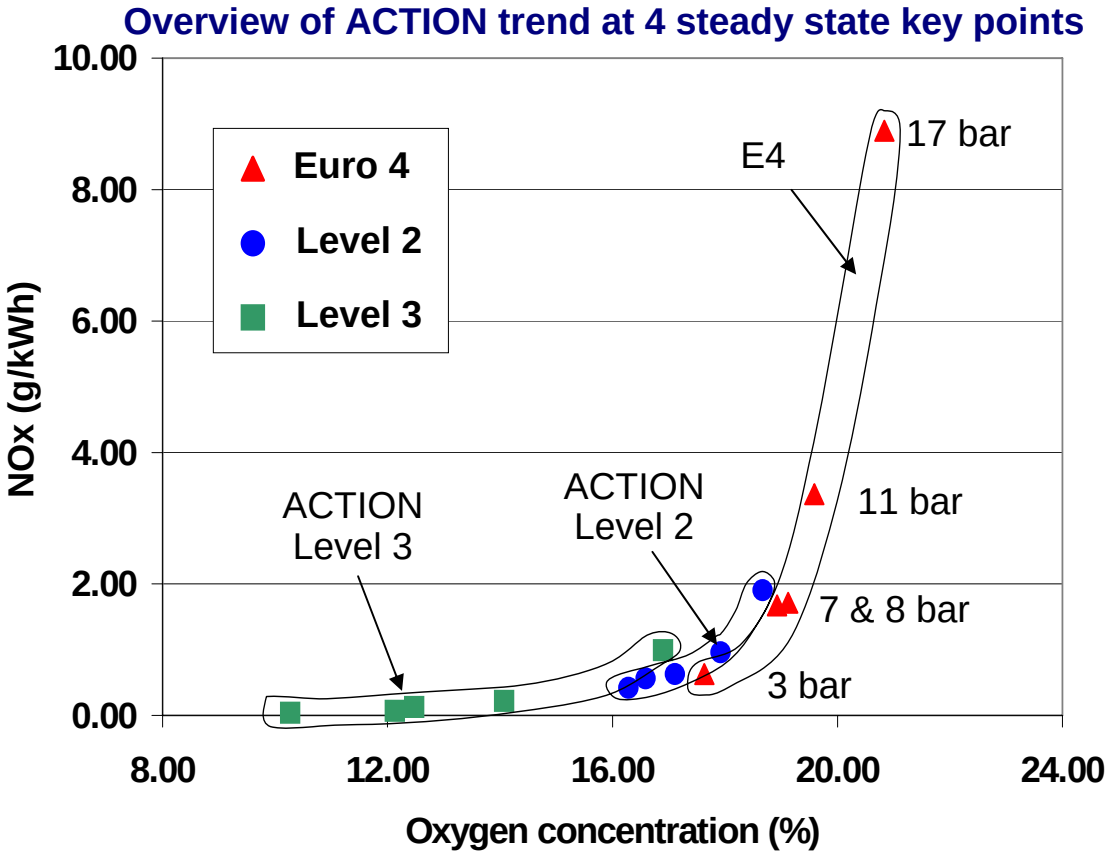


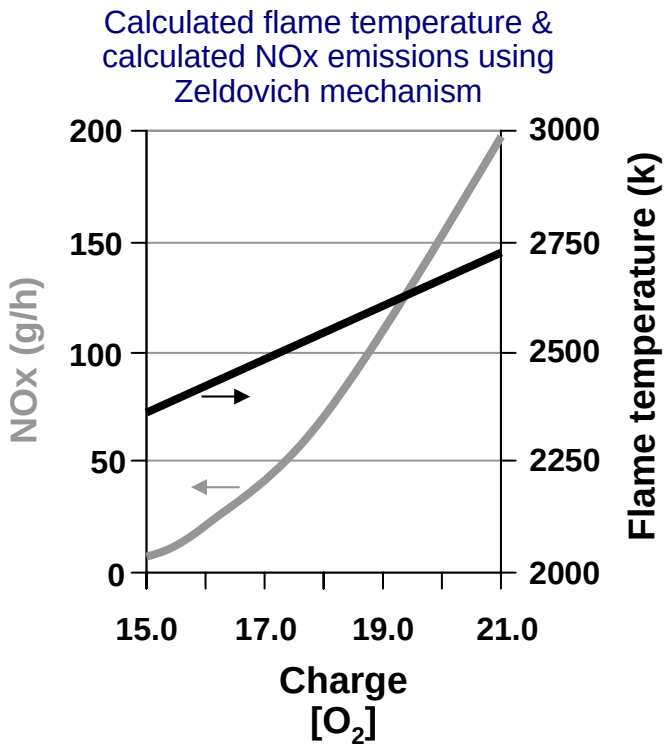




Oxygen concentration reduction by lowering air/fuel ratio and raising EGR rates is the key to lowering NOx emissions

- Reducing O_2 concentration leads to reduced maximum combustion temperatures and therefore NOx emissions

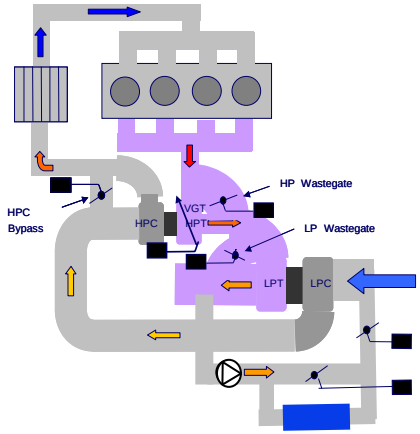


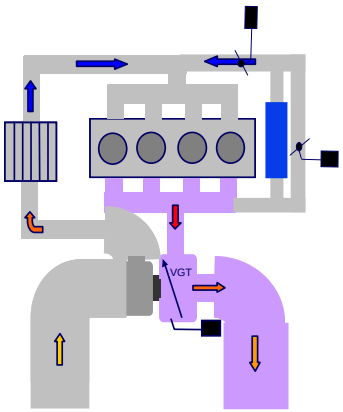


Reference: Nakayama et al. SAE 2003-01-3181

Extensive study of boost & EGR system concepts completed to assess alternative systems against Bin 5 requirements

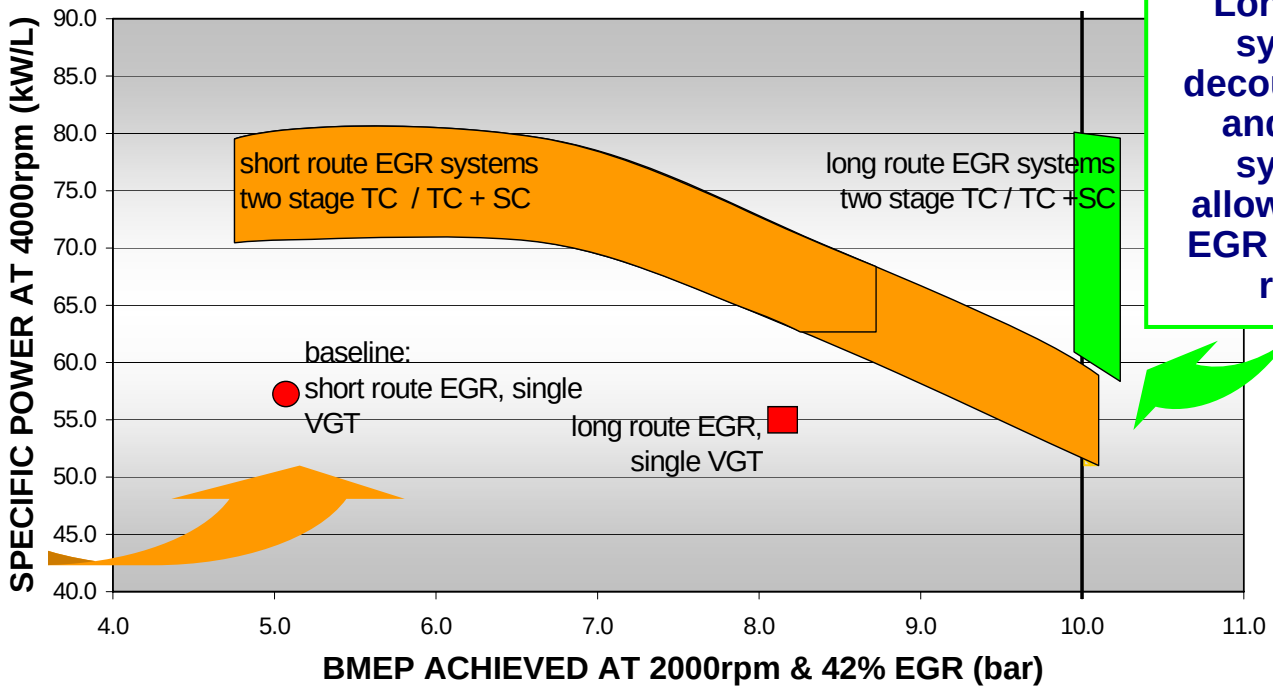
- 12+ system configurations studied including the following:
  - Single stage VGT with and without wastegate
  - Variable compressor
  - Alternative two-stage configurations
  - Turbocharger and Supercharger arrangements
  - High pressure and low pressure EGR routings





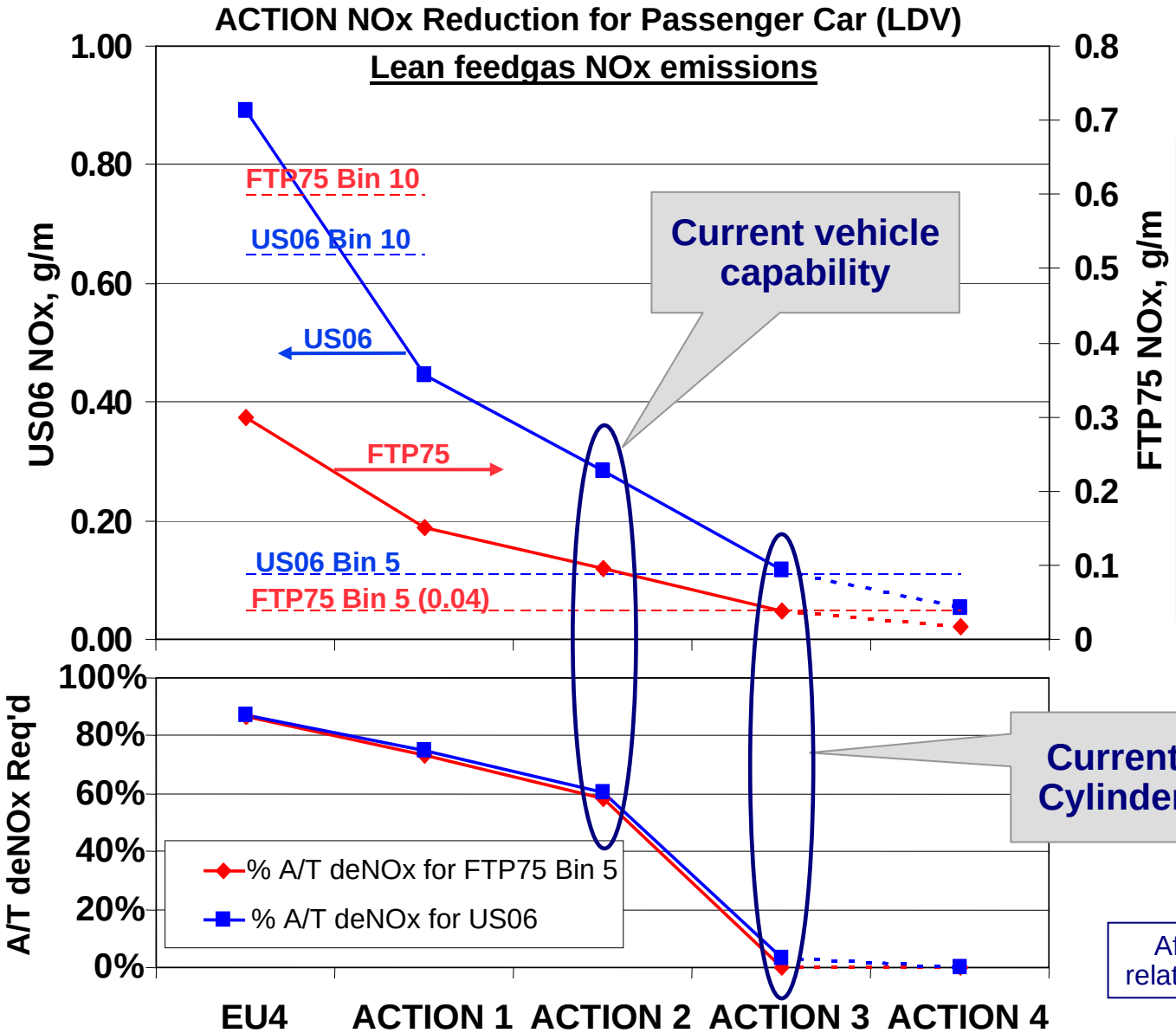
Short route systems cannot be simultaneously optimized for high EGR and high rating

PART LOAD/RATED POWER TRADE-OFF WITH HIGH EGR RATE



Long route systems decouple EGR and boost systems allowing high EGR and high rating

Ricardo target for ACTION Level 3 is Tier 2 Bin 5 without active NOx aftertreatment in a ~3500lb passenger car

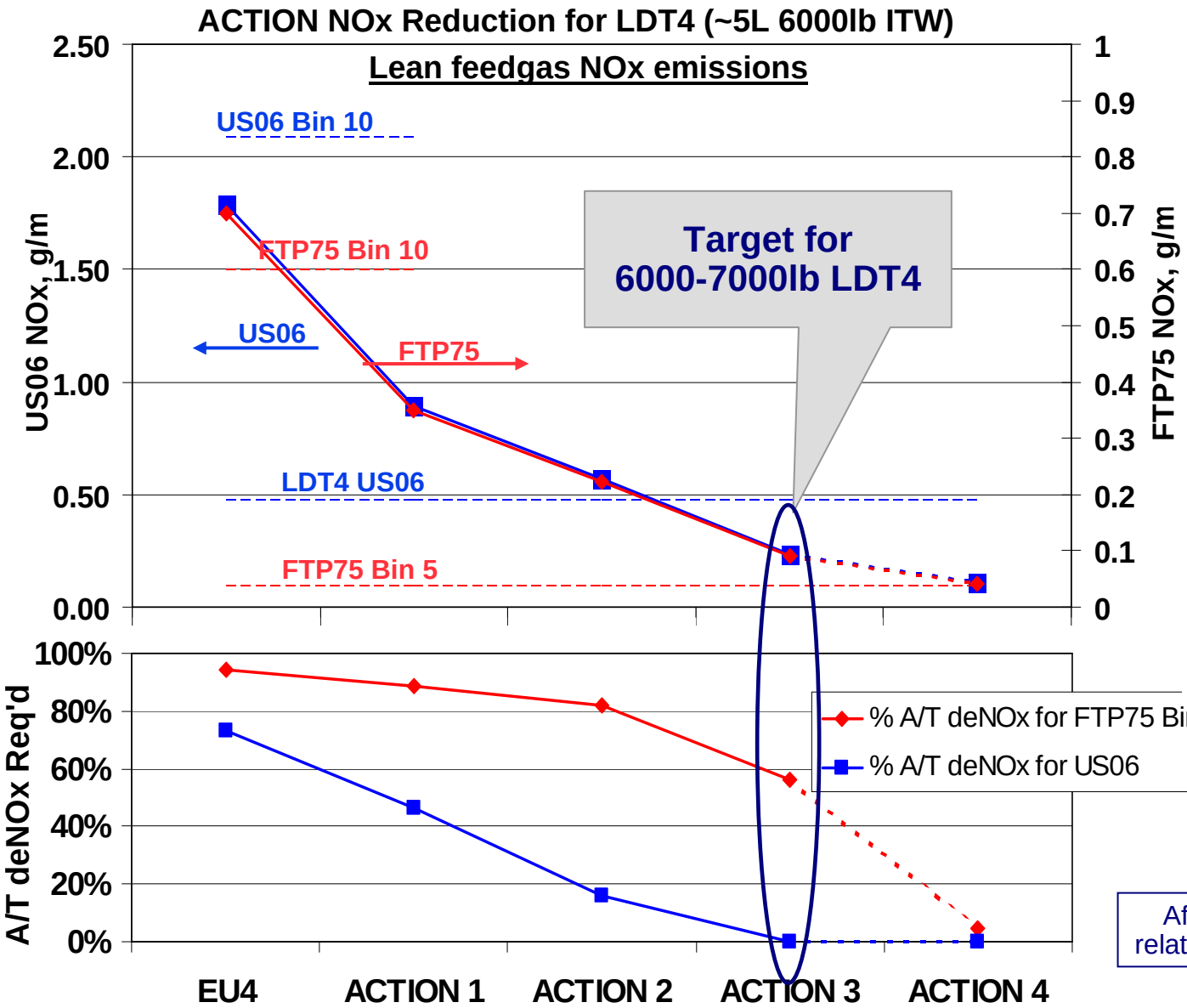


ACTION Projection

- ACTION Level 3 consistent with FTP75 Bin 5 in LDV without NOx aftertreatment
- ACTION Level 3 consistent with US06 Bin 5 in LDV without NOx aftertreatment

Aftertreatment deNOx quoted relative to lean feedgas calibration

FTP-75 becomes more challenging for LDT4, but aftertreatment deNOx could be reduced to ~60% with ACTION Level 3



ACTION Projection

- ACTION Level 3 consistent with US06 Bin 5 in LDT4
- ACTION Level 3 consistent with FTP75 Bin 5 with ~60% NOx A/T

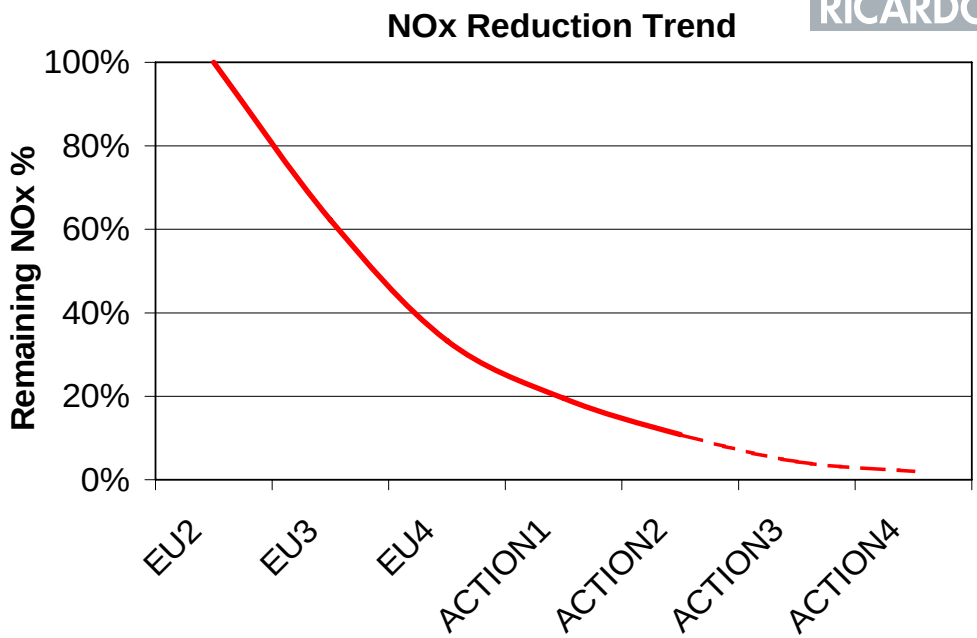
Aftertreatment deNOx quoted relative to lean feedgas calibration

Contents

- Critical challenges in developing light duty diesel solutions for the US
- Ricardo's approach to meeting the US diesel challenge
- Status update on minimum engine-out NOx development
- Summary and conclusions

Conclusions

- Huge progress in diesel emissions reduction has been made over the last ~10 years
- Highly Pre-mixed Cool Combustion offers a practical approach to further significant engine-out NOx reduction for Tier 2 Bin 5 applications



- Engine out NOx reduction combined with minimum NOx aftertreatment offers the most robust approach to Tier 2 Bin 5
  - Aftertreatment deNOx requirement reduced to <60%
  - Enables SCR solutions with service interval urea refill
  - Offers potential for robust LNT solutions and possible LNT cost reduction
  - NOx aftertreatment may be deleted for smaller vehicle applications
- Robustness (emissions variability) is becoming the key challenge
  - Closed loop combustion control solutions are under development