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2007 ENGINE HARWARE AND AFTERTREATMENT

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Introduction/Background

- HD diesel engines for trucks have achieved very significant reductions (90%+) in regulated exhaust emissions over the past 20+years.
- This has been achieved by improvements in base engine mechanical design (2v $\Rightarrow$ 4v, increased P_{max} etc.) and the combustion system (including the air handling and FIE systems ……generally without the use of aftertreatment devices
- These reductions in emissions have been achieved at the same time as significant improvements in durability, reliability and until recently, fuel consumption

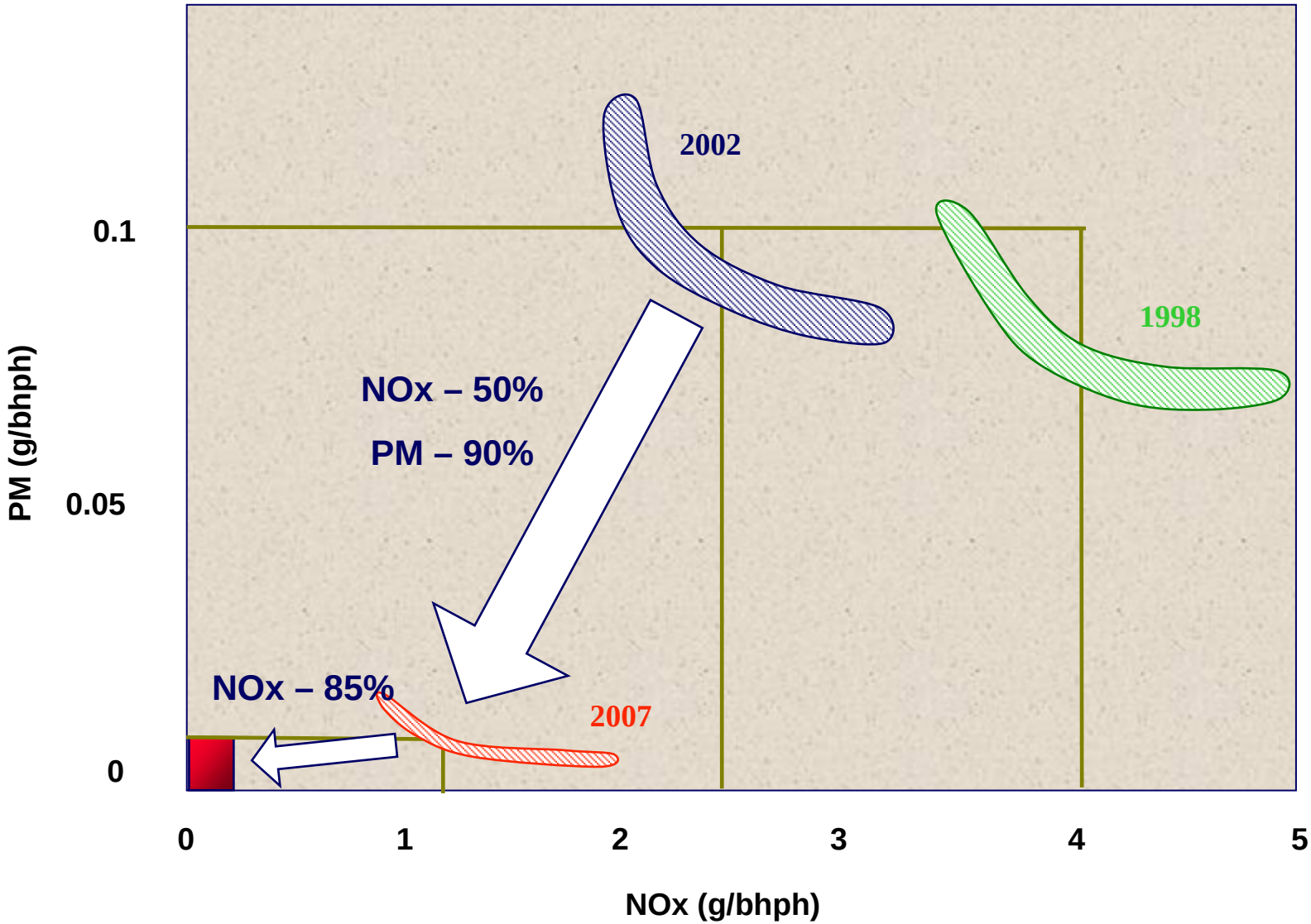
Introduction/Background (cont.)

- 2002/04 standards are generally being achieved without aftertreatment, primarily by the use of EGR
- The development of the EGR engines has been a significant technical (and marketing) challenge but one year after the introduction of these products the results are encouraging
- The emissions standards in place for the 2nd half of this decade seem to make the use of aftertreatment inevitable
  - Euro IV (2005) will use SCR
  - US 2007 emissions legislation will likely require PM aftertreatment although current work suggests that the introduction of major NOx aftertreatment could be delayed until 2010.
- The days of the non-aftertreated on-highway HD diesel engines in the US market may now finally be coming to an end….

Snapshot of Ricardo

- Leading technology partner with the engine and vehicle industry since 1918
- Specialist in powertrain & vehicle system engineering with a research & development foundation
- Independent public company headquartered in United Kingdom with technical centers in the US (Detroit and Chicago), Germany and the Czech Republic.
- Customer tailored services ranging from strategic consulting (product development focused) to product concept, design, development, release, launch and life cycle management
- 1,400 employees world wide, 85% engineers and technicians
- A global customer base with a very broad portfolio of projects
- A global business with annual turnover ~$220 million

The Challenge of 2007/2010



Meeting US 2007/2010 emissions

- There are three primary technical options for meeting the 2007/2010 NOx emission standards:
  - Increased EGR rates (2007 only)
  - Lean NOx Trap
  - Selective Catalytic Reduction
- From 2007 onwards the use of Diesel Particulate Filters to control PM seems inevitable
- 15 ppm Sulfur fuel will be the standard

Higher EGR rate approach

- Considered to be prime path for 2007 by many in the industry
- Fuel economy likely to be worse (~3-5%) cf. 2002/04 base
- Engine first cost likely to be similar to a 2002/04 (larger EGR cooler & valve)
- Regulator friendly approach: No driver intervention or infrastructure issues
- Development challenges:
  - Minimize fuel economy increase with higher EGR rate
  - Heat rejection – mitigate increase over 2002/04
  - Durability – Engine and Pm aftertreatment
  - Lubricating oil specification
  - Boosting system – 2-stage/turbocompound ?

Lean NOx Traps

- The lean NOx trap stores NOx which is then released during a regeneration mode.
  - FTP cycle efficiency can exceed 90% NOx reduction efficiency
- There are multiple system options including single or dual path approaches and combinations with DPF's and DOC's
- As with all catalyst based solutions there is a temperature range (300 – 500C) in which trap performance is optimum
  - Cold start performance will need development
- The LNT efficiency is adversely affected by the deposition of sulfur compounds. The trap needs to be 'desulfated' periodically
- Regulator friendly approach: No driver intervention or infrastructure issues

Lean NOx Trap Development Status

- Unlikely to be ready for 2007 – possible for 2010. Likely to see widespread application in LD applications first.

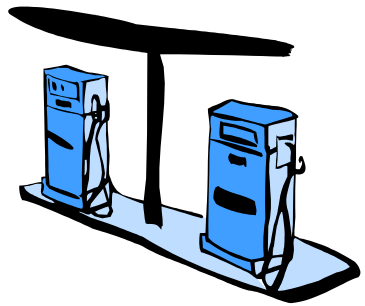
- Development challenges include:
  - Durability after many DeNOx/Desulfation cycles
  - Installed cost
  - Installed volume
  - Minimizing fuel consumption penalty
  - Controls strategy and algorithm development
  - NOx sensors ideally required to monitor trap fill state and performance

- Lean/rich cycling of the engine places additional demands on the engine, turbocharger and EGR system.
  - Long term engine durability will need to be assessed and probably developed to make this approach fully production compatible

Selective Catalytic Reduction (SCR)

- The SCR process makes use of a nitrogen compound, (Ammonia or Urea) reacting with NOx over a catalyst to produce water and nitrogen
- The technique is well established in NOx control from stationary industrial plant, engines and turbines
- The reduction reaction is dependent upon the catalyst formulation, the NOx level, the gas temperatures and the amount of urea injected. A variety of different catalyst materials are available, these tend to demonstrate different operating temperature windows
- NOx reductions of greater than 90% are possible with appropriate levels of urea injection, exhaust gas temperature, oxidation catalyst etc.
- The very effective NOx reduction from SCR promises the best fuel consumption of the candidate techniques and also smaller/more durable DPFs due to the lower engine out Pm resulting from a more advanced injection timing

Urea delivery network



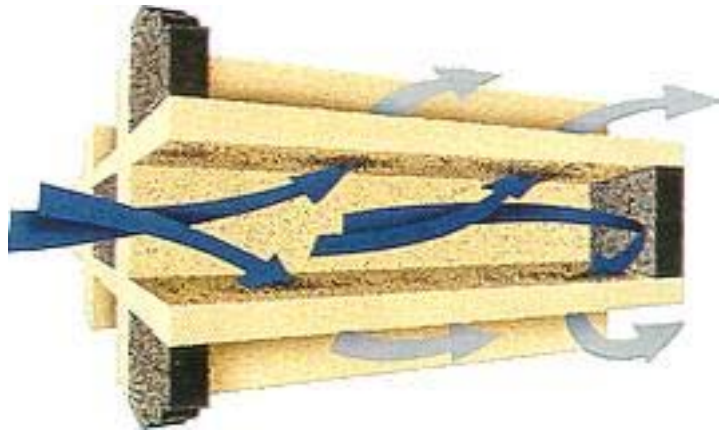
- For an SCR solution to be adopted, the urea needs to be both available at the point of use and reliably priced.
- Little concern about meeting the supply requirement.
- To date no industry-wide consensus to establish the supply and retail distribution infrastructure. It will require an early commitment from all of the stakeholders to make this happen in time for 2007.
- Centrally fuelled or depot based fleets are a possibility but these may be affected by uncertain resale value of the trucks
- The final retail price of urea is not yet clear, estimates vary for different size refuelling operations, geographic locations etc. between $0.50/gall and well over $3/gall and this price has a strong influence on the overall economics of SCR

SCR Development Status

- Prime path for EURO IV (OCT 2005) for European OEMs
- Additional controls are required to regulate the urea injection
  - Need NOx and temperature mapping to know when to inject urea.
  - Too much urea leads to NH3 slip. Too little leads to NOx slip.
  - Down stream oxidation catalyst to convert any burn NH3 slipped into NOx.
- SCR catalysts and urea tank need to be accommodated on the vehicle
- Question over in-service compliance and OBD – requires active involvement of the driver + NOx sensor

Diesel Particulate Filters

- Exhaust gas enters the blocked channels and is forced through porous walls - Soot material trapped on walls



- >90% soot removal possible but a periodic regeneration of the filter is required to remove soot
- Filter material: SiC or cordierite
- Retrofit program currently in place although primarily in 'DPF-friendly' applications i.e. with exhaust temperatures above at least 250C for much of the duty cycle.

Regeneration of DPFs

- Regeneration (removal of collected soot) is achieved via soot oxidation
  - Continuous regeneration e.g. CRT™ or catalyzed filter
  - Active regeneration (forced event)

- Active regeneration relies on O_2 - soot reaction which will occur at high temperatures (>600°C). Options to achieve active regeneration include:
  - Electrical heating
  - Exhaust temperature management (e.g. VVT or Cylinder deactivation)
  - Warm-up DOC - NO oxidation to NO_2 improves PM combustion efficiency

- Uncontrolled soot oxidation is a concern $\Rightarrow$ can cause substrate meltdown

DPF's - Development Status

- Likely to be in common use as an OE fitment by 2007
- Development challenges include:
  - Improving long term durability
  - Optimizing regeneration procedures (probably active)
    - Fill State Prediction/Modeling
    - Uneven distribution of ash/soot
    - Pressure sensors not the best method to determine fill state
  - Ash build-up and removal
  - Prevention of filter breaking

There are a number of questions which apply to all potential solutions

- Installed volume
- Installed cost
- Installed weight
- Real world durability (need to be compliant after 435,000 miles)
- Fuel economy impacts
- Combinations of aftertreatment to jointly control Pm and NOx
- OBD issues including sensors (e.g. NOx, NH**3)**
- Development of robust and practical testing protocols
- Unregulated emissions (Aldehydes, Aromatics, CH**4,** N**2**O etc.)

Development issues

- LNT's
  - DeNOx and Desulfation strategies
  - Emissions during the regenerations
- SCR
  - Urea infrastructure and costs
  - EPA acceptance
  - NH3 slip
- DPF's
  - Active regeneration strategies
  - Ash removal, handling and disposal strategies
  - Alternative substrate constructions i.e. non wall-flow

Summary

- Meeting 2007 NOx targets appears to be technically achievable by three difference routes
  - Higher EGR rates – will require further development but current results are encouraging. Added 1st cost should be limited but the approach will place higher heat rejection demands on the vehicle and will result in a fuel consumption penalty compared to the 2002 products
  - SCR is a well proven, technically feasible solution which will result in a fuel consumption improvement compared to the 2002 product. The urea infrastructure issue and EPA agreement are key issues
  - LNTs have the technically feasibility of being part of a 2007 solution, but given the capability of the EGR solution and the relative immaturity of LNTs, they are more likely to be considered as a part of a 2010 solution.

Summary (cont.)

- Meeting 2007 PM emissions levels will require the use of DPFs. The technology is maturing but there is development still to be completed

- There will not be a ‘one size fits all’ approach to meeting 2007 and we can expect to see a variety of different technical solutions being developed as the truck and engine OEMs work together with their supplier base to combine and optimize the systems

- OEMs will be considering how to meet the 2010 emission levels as they firm up their plans for 2007. If at all possible, the desire will be to make the 2007 engine a stepping stone for the 2010 solution