EPA ENGINE IMPLEMENTATION WORKSHOP - 6/7 August 2003

2007 TECHNOLOGY PRIMER

Graham B. Weller

Ricardo Inc.

Contents

- **Introduction/Background**
- Summary of main points of the 2007/2010 legislation
- Discussion of main technical options
  - –Higher EGR rates
  - –Lean NOx traps
  - –Selective Catalytic Reduction
  - –Diesel Particulate Filters
  - –Other 2007/2010 options
- Cost Analysis
- Base Engine Design Changes
- Development timetables
- Summary

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
- An impressive global customer base with a very broad portfolio of projects
- A global business with annual turnover ~$220 million

Introduction/Background

- HD diesel engines for trucks have achieved very significant reductions in exhaust emissions over the past 20+years.

- This has been achieved by improvements in:
  - The combustion system
    - fuel injection equipment (increased injection pressures & control)
    - air handling (NA ⇒ TC ⇒ TCA ⇒ Turbocompound/2-stage)
  - Mechanical design
    - 2V ⇒ 4V
    - increased P_{max},
    - reduced oil consumption etc.

…..generally without the use of aftertreatment devices

- These reductions in emissions have been achieved at the same time as significant improvements in fuel consumption, durability and reliability

Introduction/Background (cont.)

- US 2002/04 standards are generally being achieved without aftertreatment, primarily by the use of EGR

- As a principle engine/truck OEM's and operators would prefer to avoid having to use aftertreatment (cost, space, durability etc.) but the days of the non-aftertreated on-highway HD diesel engines in the US market may now finally be coming to an end….

- The emissions standards in place for the 2nd half of this decade now seem to make the use of NOx and/or Pm aftertreatment inevitable
  - Euro IV (2005) is expected to see the first mass market use of SCR for mobile applications
  - 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 development of EGR solutions has presented multiple technical (and marketing) challenges

- The major technical development challenges have been:
  - Development of reliable EGR components
  - Development of robust EGR control systems
  - The increased heat rejection to the truck cooling pack
  - Limitation on engine rating and fuel consumption

- Convincing the market of the technical readiness of these products has been a challenge but real life operating experience is now becoming available and the performance of the 2002 engines has been encouraging

While legislation is a key driver, there are many others acting upon the players in this global industry

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Legislation

- Regionally specific emissions legislation
- Regionally specific noise legislation
- Recycling legislation (e.g. 80% @ 2020 in EU)
- Local legislation
- Manufacturing environmental, health & safety
- OBD
- Renewable fuels compatibility
- National energy security concerns

Competitive position

- Global
- Scale economy
- New features
- Price pressure

Customers

- Product efficiency
- Internationalization
- Vehicle utilization
- Vehicle weight
- Operating costs
- Cost of capital
- Total business equation

The Global Market

- Differences between US,EU and Asian markets
- Manufacturing location choices

Technology

- Telematics
- Hybridization
- New combustion systems
- New materials
- Integrated control systems

Vehicle Operator Needs

- Life Cycle Profitability
  - Initial price
  - Resale value
  - Fuel consumption
  - Maintenance needs and costs
  - Reliability and durability
- Driver / user environment
- Safety

Product

- Reliability (warrantee costs)
- Refinement
- Emissions compliance
- On Board Diagnostics (OBD)
- Performance (power, torque)
- Fuel consumption
- Package (weight, volume)
- Maintenance intervals (cost)
- Product cost
- Durability
- Alternative Fuels
- Recyclability
- Shift comfort

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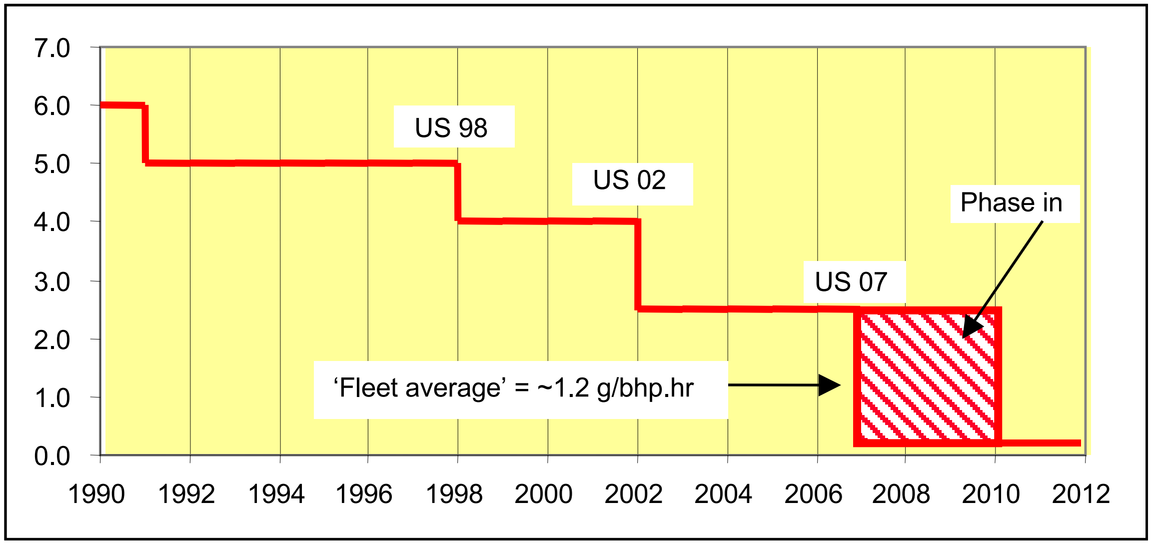
NOx and Emissions Legislation

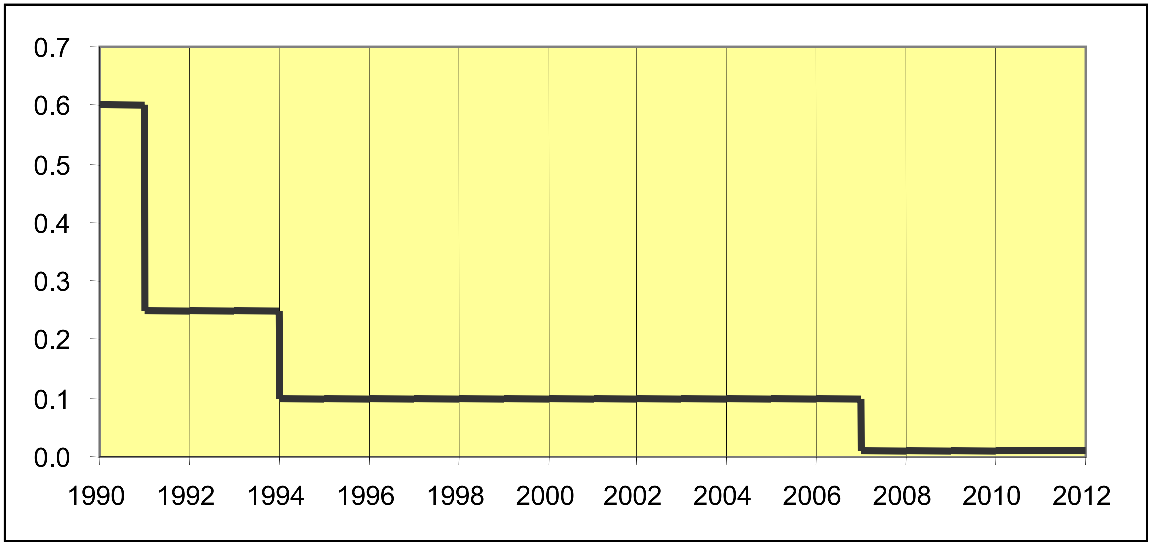
NOx

(g/bhp-hr)

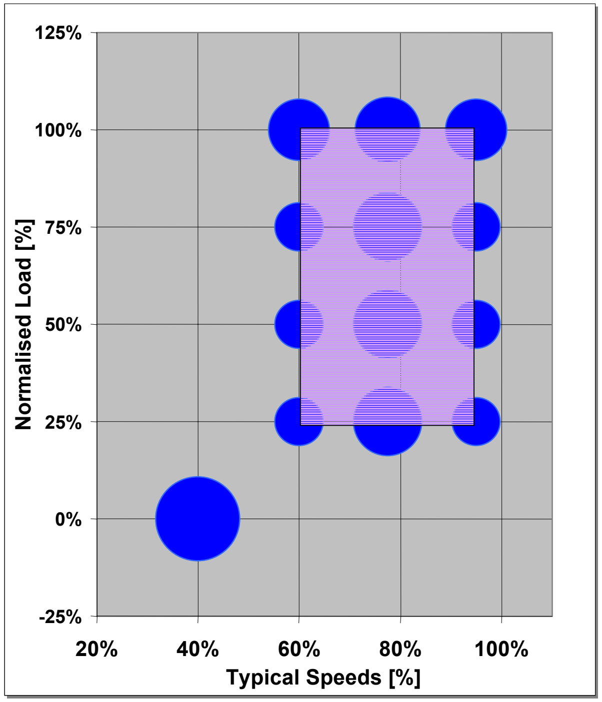


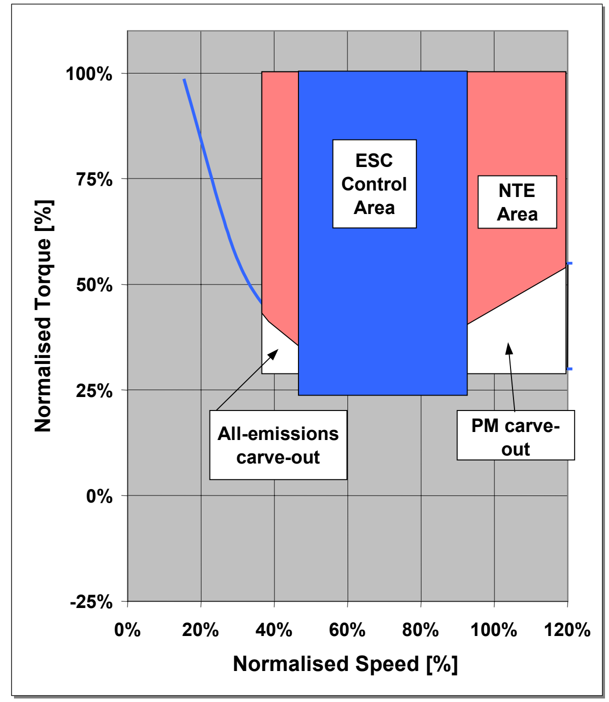
PM

(g/bhp-hr)



Exhaust emissions – US test cycles





Supplementary Emissions Test (SET)

USA Heavy Duty Transient Test Cycle (US-FTP)

Typical “Not To Exceed” Zones (NTE)

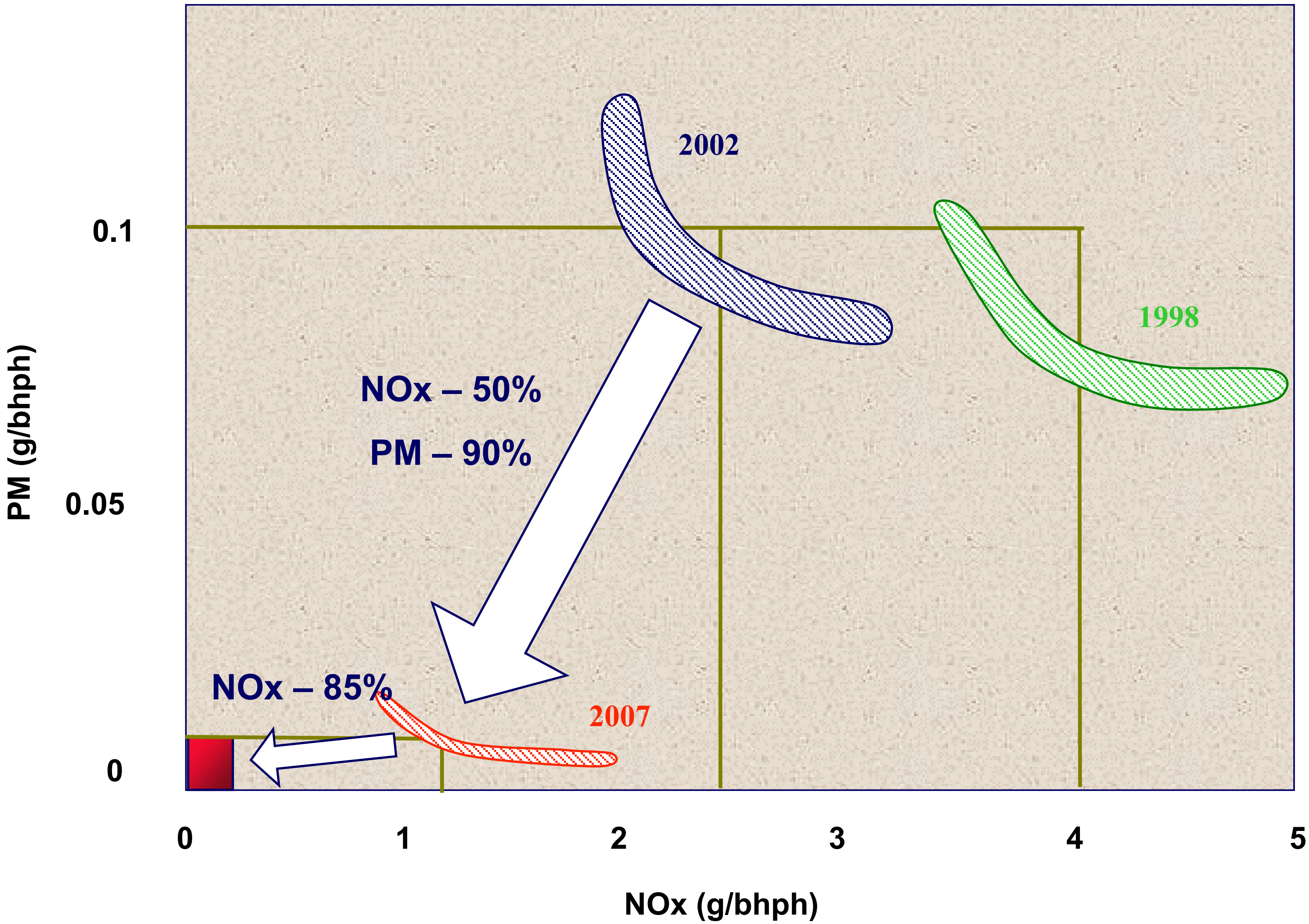
Other Aspects of US2007

- Exhaust aftertreatment technologies are expected to be required to meet the new standards but these are generally not tolerant to sulfur. Therefore, as a “technology enabler”, the maximum allowable sulfur level in highway diesel fuel will be reduced to 15 ppm down from 500 ppm today. This low sulfur fuel will introduced during 2006 .

- The 2007 standards eliminate an existing exception regarding the emissions of crankcase gases which currently applies to turbocharged engines

- During the phase-in manufacturers will be able to participate in an averaging, banking and trading (ABT) program

The Challenge of 2007/2010



Aftertreatment vs. Emissions Control System

- The term 'aftertreatment' suggests a 'stand-alone' device

- Emission control system more accurately describes the required approach. To be effective this system needs to be a well developed combination of:

  – The combustion system: combustion bowl, intake ports
  – The fuel injection equipment: timing/pres/rate/# of injections/nozzle design
  – The fuel: sulfur content, centane #
  – The lubricating oil: weight, sulfur content, ash content
  – The overall control strategy

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Approaches to 2007/2010 HD emissions standards

- There are three primary technical options for meeting the US 2007/2010 NOx emission standards:
  - High EGR rates (2007 only)
  - Lean NOx Trap
  - Selective Catalytic Reduction

- From 2007 onwards the use of Diesel Particulate Filters to control PM seems inevitable

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EGR - Methodology

- Exhaust Gas Recirculation (EGR) introduces exhaust gas into the intake of the engine replacing some of the air. This has the effect of reducing NOx emissions by reducing the in-cylinder gas temperatures: NOx production is very temperature sensitive
- A major development challenge for HD on-highway truck engines is to force the hotter exhaust gas into the intake air without costing too much loss of volumetric efficiency or fuel economy.
- The precise control of the EGR flow, effect of the EGR upon engine durability and development of appropriate lubricating oil specifications have all been addressed in the development of the 2002/04 engines
- Recent work by Ricardo, and others, is indicating that a very well developed combustion system, using perhaps 50 - 60% higher levels of EGR than the 2002 engines could achieve the 2007 NOx levels without NOx aftertreatment

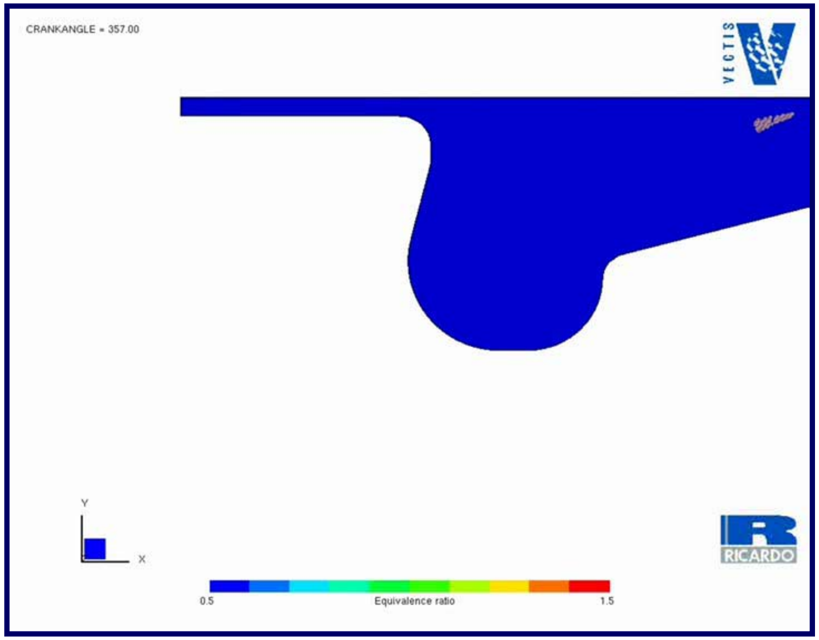
Higher EGR rate approach

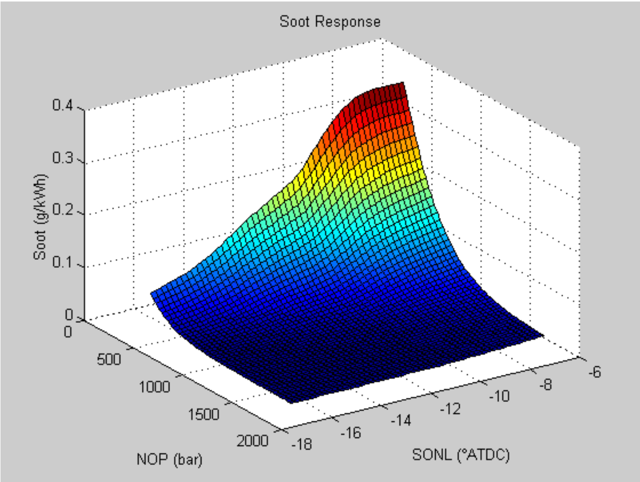
- Increasingly becoming considered prime path for 2007 by many in the industry
- Field experience with 2002/04 EGR engines is promising
- Fuel economy likely to be worse (~3-4%) cf. 2002/04 base
- Engine first cost similar to 2002/04 (larger cooler & valve)
- Regulator friendly approach: No driver intervention or infrastructure issues
- Development challenges/questions
  - Combustion system (see next slide)
  - Heat rejection – mitigate increase over 2002/04
  - Durability – Engine and aftertreatment
  - Boosting system – 2-stage/turbocompound

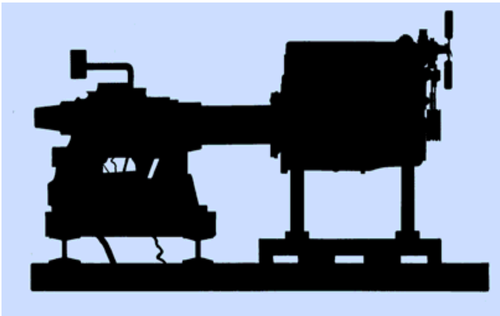
The development of a combustion system capable of operating at higher levels of EGR will require detailed multi parameter optimization of the all aspects of the combustion system

FIE Parameters

- Pilot quantity
- Post quantity
- Pilot interval
- $SONL_{main}$
- Post interval
- $Pilot_{NOP}$
- $Main_{NOP}$
- $Post_{NOP}$







High pressure, short route EGR systems dominate the on-highway market

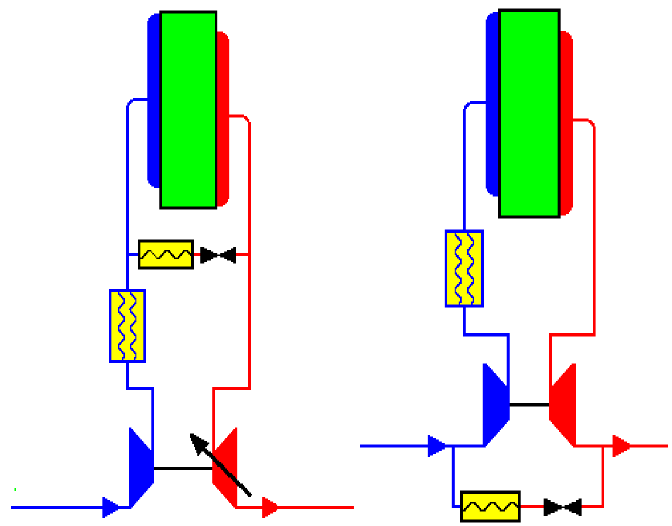
- Systems introduced to the market place to date have been high pressure (short route) systems (Cummins, DDC, Mack, MAN, RVI)
  - The use of venturi assisted EGR transfer is now in the market place on Cummins engines
  - The use of pulsed EGR (non-return valves) is now in the market place with Volvo and Deutz
- Increases in the maximum EGR achievable with high pressure systems could be facilitated with
  - Increased boosting capability
  - Application of turbocompounding
  - Application of integral EGR pumps
  - Application of variable geometry compressors
- Low pressure (long route) EGR systems may be of mainstream interest once particulate filtration is commonplace
- Internal EGR will be of further interest to support higher levels of EGR and HCCI combustion development, but is strongly linked to the application of VVA systems.

Short vs. Long route EGR

- DPF is an enabler for long route EGR

- Benefits - long route
  - A negative deltaP is not required
  - Potentially less difficult to control
  - Fixed geometry turbine and WG may work, application dependent

- Drawbacks - long route
  - Physically larger EGR cooler
  - May require inlet throttling / exhaust backpressure control / venturi
  - Transient response



Short Route   Long Route

EGR - Conclusions

- An approach to 2007 emissions building upon the EGR techniques being widely applied for 2002 shows promise and is being actively considered by many OEMs

- At the moment there is no single technology path that has been identified to achieve this result - different approaches are being investigated considering many different components

- The development of these products will require the use of advanced design of experiments techniques in combination with traditional engine test work and truck field trial work to optimize the overall system

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Lean NOx Traps - Methodology

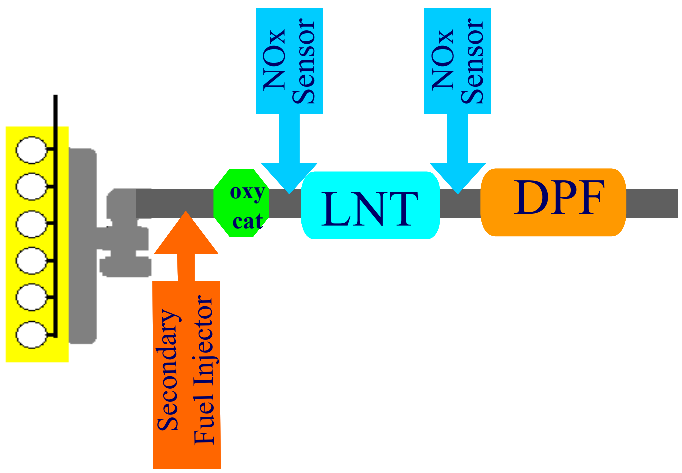
- The lean NOx trap (aka NOx Adsorber Catalysts) stores NOx which is then released during a regeneration mode (high temperature, reducing atmosphere) - this is not a normal mode of operation for a diesel engine

- There are several system options including single or dual path approaches

- Long term trap efficiency is adversely affected by the deposition of sulfur compounds (even with 15ppm sulfur fuel) and the trap therefore needs to be 'desulfated' periodically. This is achieved by an more extended/extreme version of the regeneration process

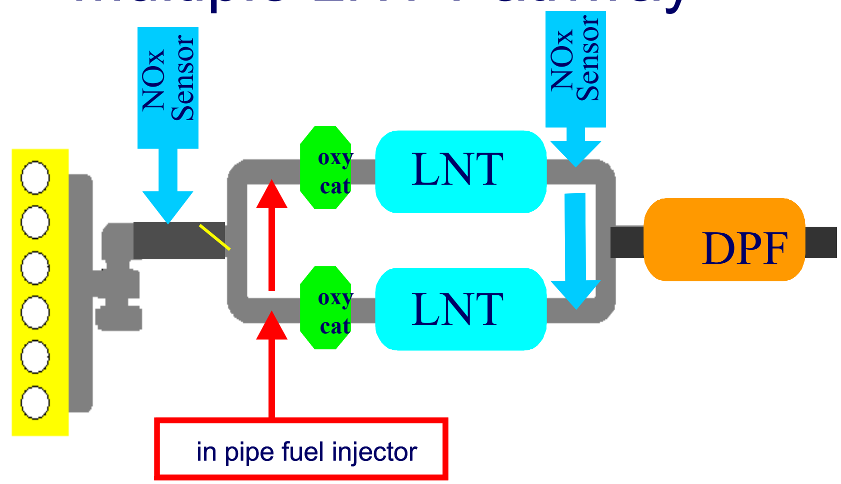
Single vs. Dual Path LNT's

Single LNT Pathway



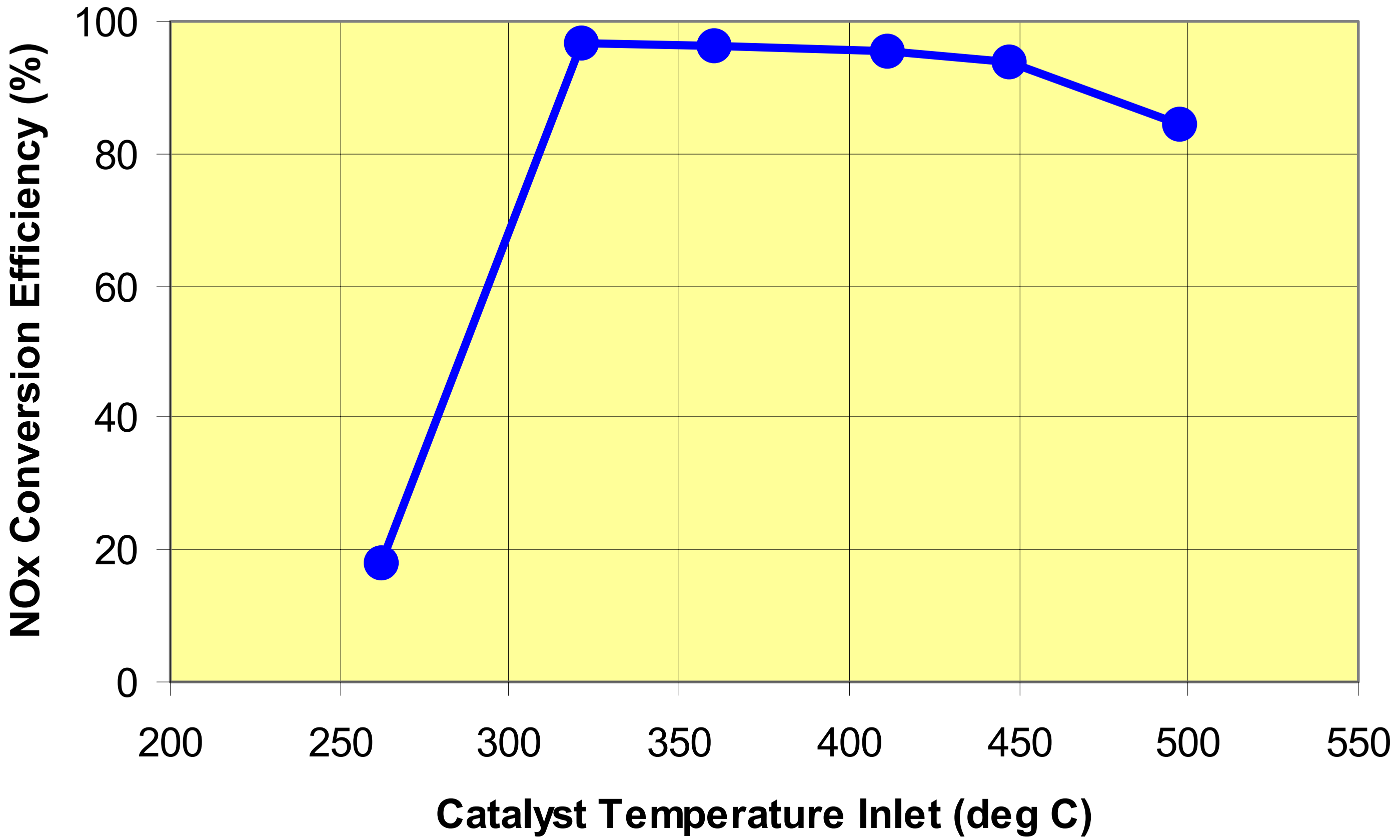
- ❑ Requires entire exhaust to go rich
  - – EGR main route to enrichen
  - – In-cylinder fuel injections
  - – in-exhaust pipe fuel injections
- ❑ Less catalyst volume

Multiple LNT Pathway



- ❑ Most flow through adsorption leg
- ❑ Limit flow through regeneration leg
- ❑ Diverter valve switches flow between legs
- ❑ Requires only part of exhaust to go rich
- ❑ Larger catalyst volume

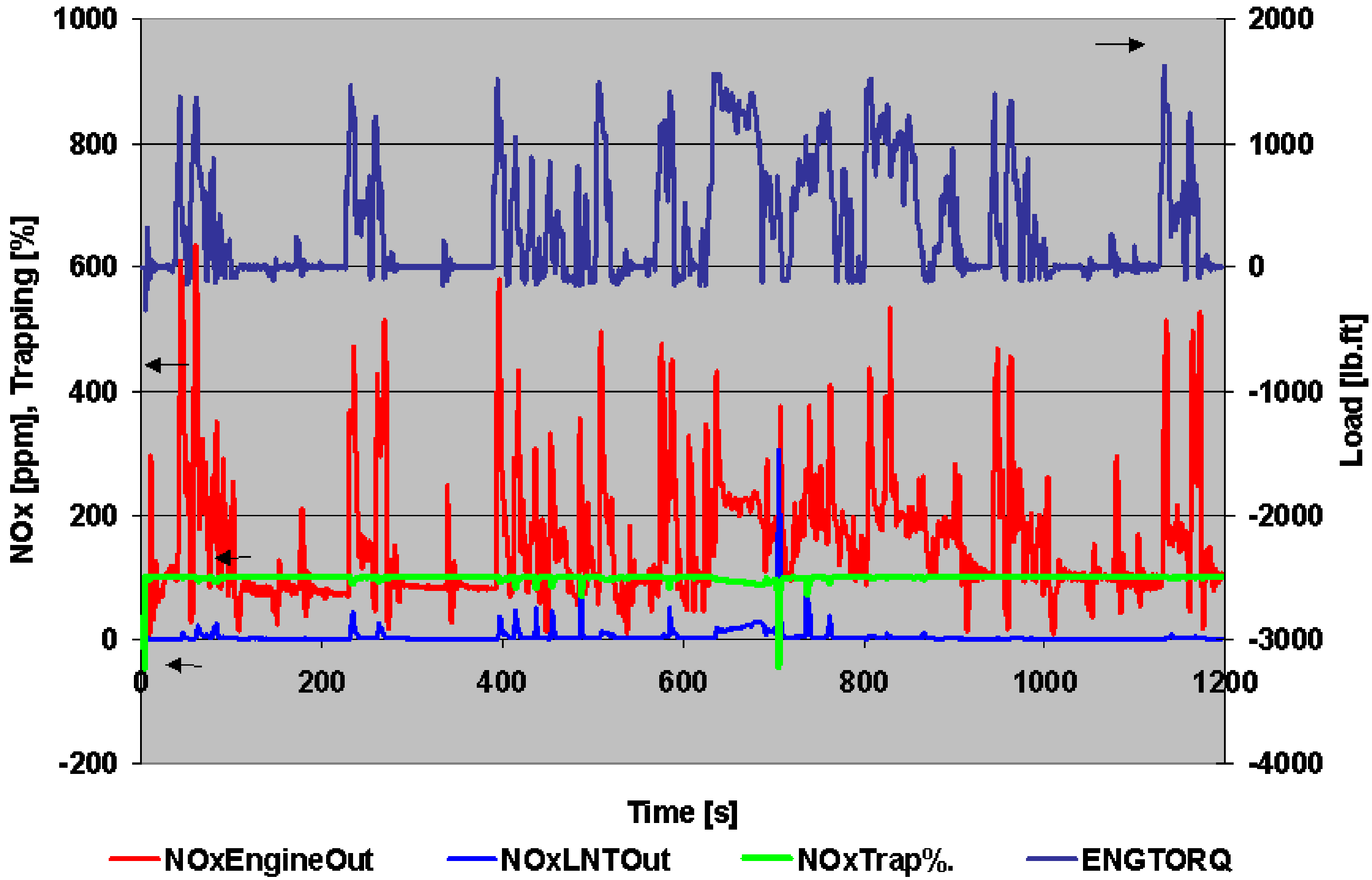
As with all catalysts NOx conversion efficiencies vary as a strong function of catalyst temperature



Source DECSE

Preliminary Results from a project being conducted by Ricardo as a part of the APBF program managed by NREL

- Hot start FTP cycle trace with a Single path NOx Adsorber



LNT issues

- Subject of much industry activity and investigation
- Fuel economy penalty still to be established but likely to be 3 – 5%
- Regulator friendly approach: No driver intervention or infrastructure issues
- Unlikely to be ready for 2007 – possible for 2010, likely to be applied in lighter duty applications first
- Development challenges:
  - Durability after many DeNOx/Desulfation cycles
  - Installed cost
  - Installed volume

Lean NOx Trap Conclusions

- High NOx conversion efficiency
  - FTP cycle efficiency can exceed 90% NOx reduction efficiency
  - Cold start performance will need development
- Complex/bulky system
  - Switches between lean/rich atmospheres required sophisticated controls and algorithm development
  - NOx sensors ideally required to monitor catalyst performance
  - Fuel consumption penalty likely due to rich operation
- Lean/rich cycling of the engine places additional demands on the engine, turbocharger and EGR system.
  - The effect on engine durability will need to be mitigated by additional mechanical development to make this approach production compatible
- Requires very low fuel Sulfur levels to reduce the frequency of desulfation events

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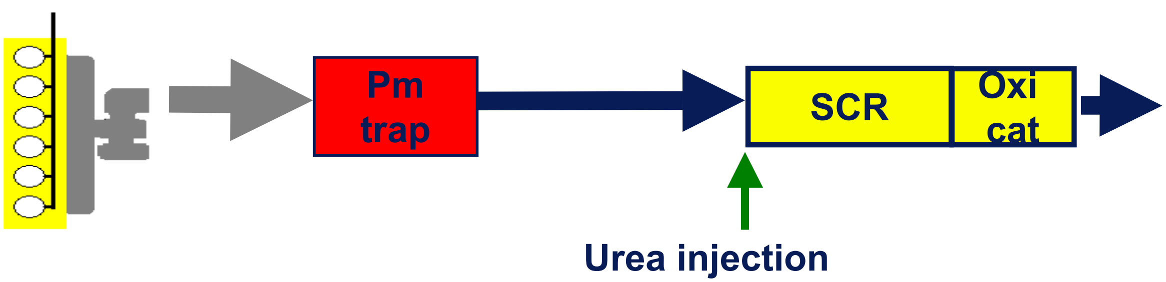
SCR - Methodology

- The SCR process makes use of a nitrogen compound, (Ammonia or Urea) reacting with NOx over a catalyst to produce water and gaseous 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



SCR demonstration project performed by Ricardo sponsored by the Association for Emissions Control by Catalyst (AECC)

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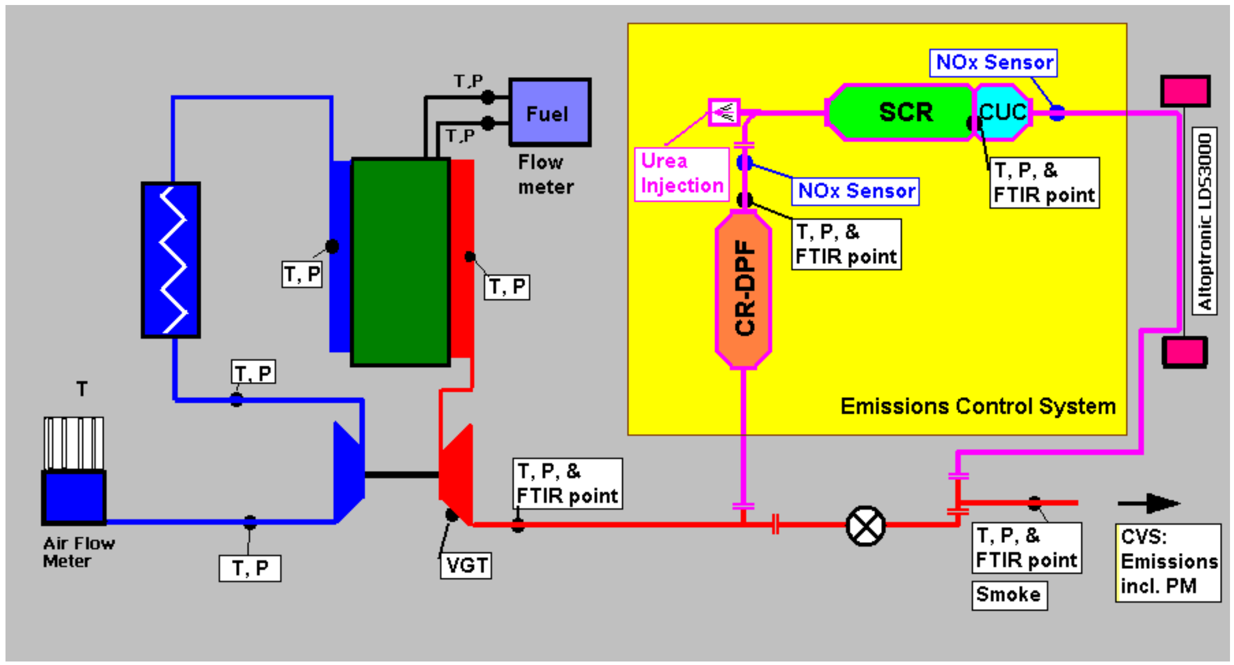
- Engine: 7.8L, 6 cylinder, 295kW, 1280Nm
- Aftertreatment system
  - DPF-SCR-DOC
- Conversion during ETC after 1000h ageing
  - CO 76%
  - HC 99%
  - NOx 85%
  - PM 83%

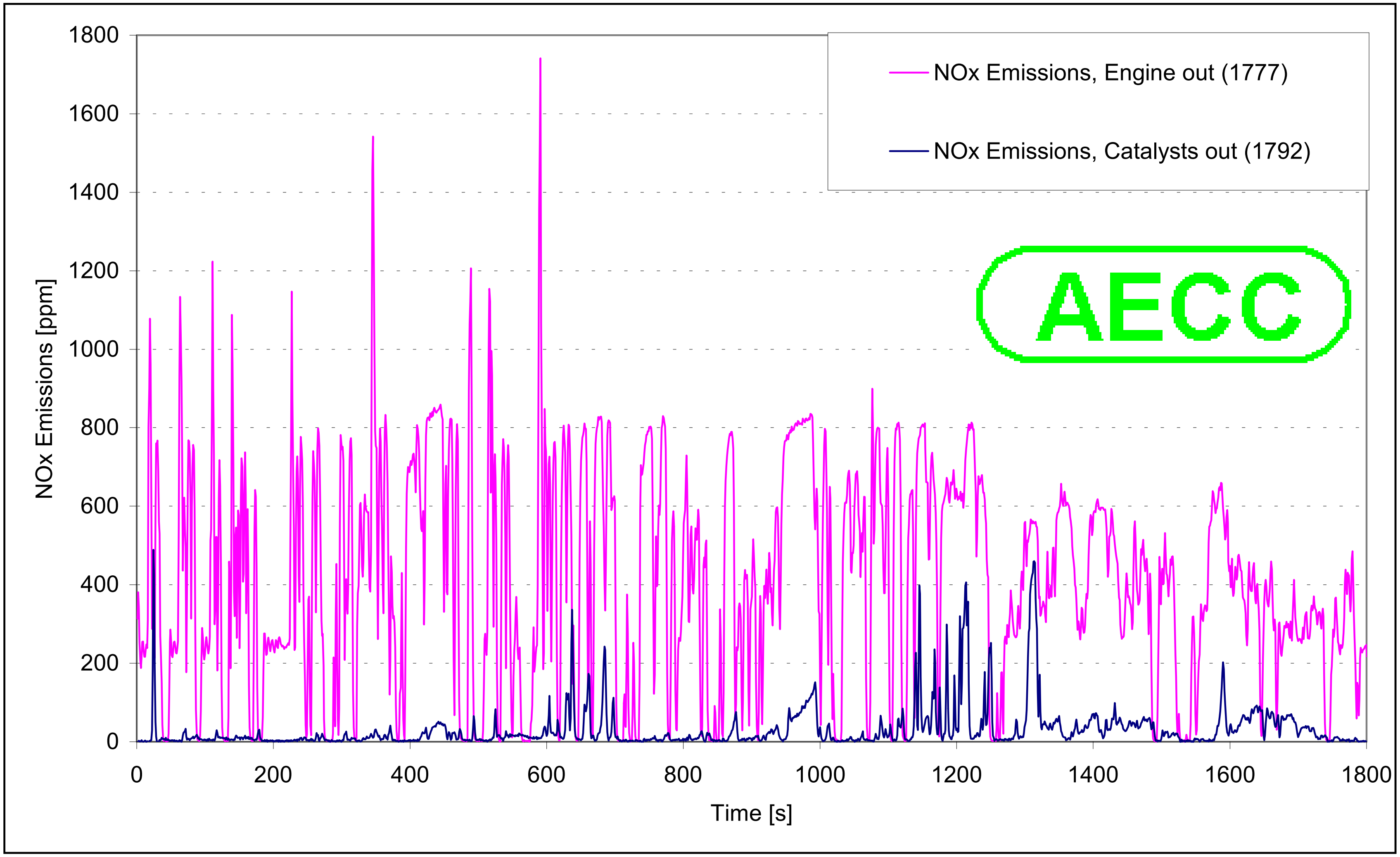


AECC

Results published at FISITA Conference in June 2002:

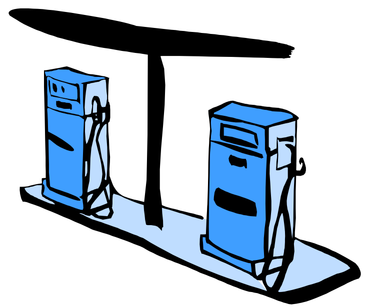
F02E310 Investigation of the Feasibility of Achieving Euro V Heavy-Duty Emission Limits by Advanced Exhaust Gas Aftertreatment

ETC Tests at 1000h: NOx Engine Out vs. Catalysts Out



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.



- Generally little concern about meeting the supply requirement.
- No industry-wide consensus to establish the supply and retail distribution infrastructure. It would require full commitment from all of the stakeholders to make this happen in time to support an SCR solution to 2007.
- 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

SCR Conclusions

- High NOx conversion efficiency (80%+ feasible)
- Smallest impact on base engine – fuel economy improvement possible
- 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 NH_3 slip. Too little leads to NOx slip.
  - Down stream oxidation catalyst to convert any burn ammonia slipped into NOx.
- SCR catalysts and urea tank need to be accommodated on the vehicle
- Infrastructure issues would need to be agreed before SCR could become a prime technology path, 2007 seems unlikely, 2010 a possibility
- Centrally fuelled or depot based fleets are a possibility but these may be affected by uncertain resale value of the trucks
- Relatively well developed and production robust approach
- Overall economics will be strongly influenced by urea price
- Question over in-service compliance and OBD – requires active involvement of the driver + NOx sensor

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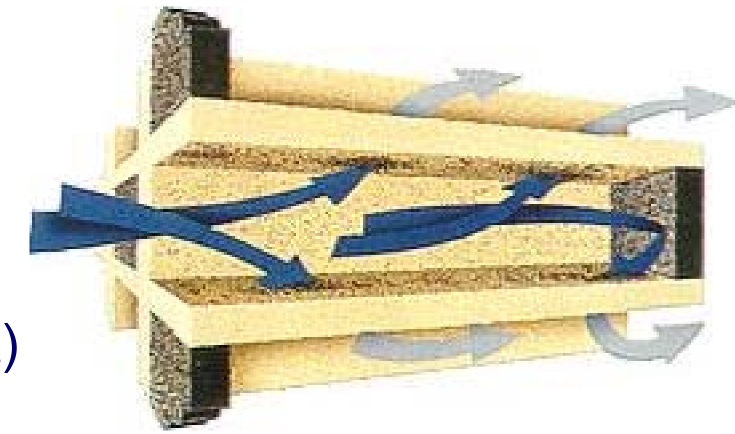
Diesel Particulate Filters - Methodology

Exhaust gas enters the blocked channels and gas is forced through the porous walls



- Soot material trapped on walls >90% soot removal possible
- Regeneration (removal of collected soot) is achieved via soot oxidation
  - Continuous regeneration (passive event)
    - Pre-filter oxidation catalyst (CRT™)
    - Catalyzed filter
  - Active regeneration (forced event)
- Uncontrolled soot combustion creates significant heat
- Filter material: SiC or cordierite
- Retrofit program currently in place – DPFs are a proven technology, the major challenge now is to ensure their suitability for all potential applications

Continuously regenerating DPFs

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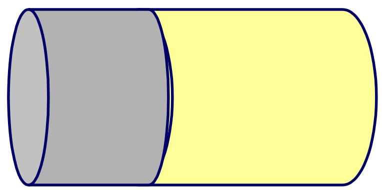


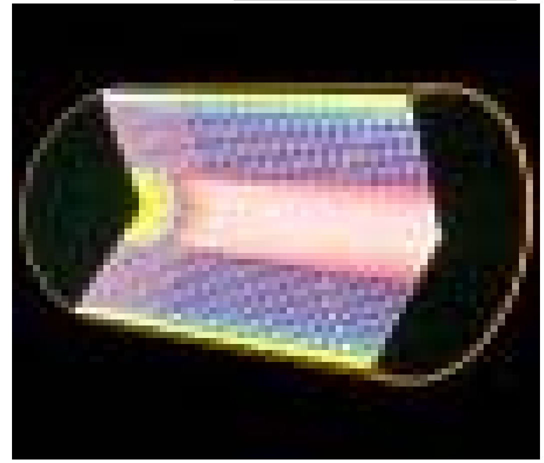
CONTINOUS REGENERATING TRAP

- CRT™ by Johnson Matthey
- Front oxidation catalyst for NO $\rightarrow$ NO_2
- Front substrate not a trap - open channels
- Relies on NO_2 - soot reaction
- Occurs at low temperatures (>250°C)
- $SO_2 \rightarrow SO_3$ occurs
- Low sulfur fuel needed; avoid SO_4 make

CATALYZED TRAP

- Filter has washcoat on surface
- Washcoat adds to backpressure
- Uses NO_2 - soot reaction and "active oxygen" to burn soot.
- Less reliant on NO_2/soot ratio
- Sulfate make (tail pipe emission) also an issue
- Engelhard's DPX™ an example

Active regeneration of DPFs



- Active regeneration relies on O_2 - soot reaction which will occur at high temperatures (>600°C)
- Runaway oxidation an issue ⇒ can cause substrate meltdown
- Options to achieve active regeneration include:
  - Electrical heating
    - Requires significant amount of electrical power
    - Pre-heater less efficient but smaller
  - Exhaust temperature management
    - VVT
      - Camless
      - Lobe shifting etc…
    - Cylinder de-activation
      - Relatively simple device
      - Lost motion technology most common
  - Warm-up Catalyst (DOC)
    - NO oxidation to NO_2 improves PM combustion efficiency
    - Fuel penalty

Diesel Particulate Filters - Issues

- Filter plugging
  - Ash build-up
  - Soot build-up
- Fill State Prediction/Modeling
  - Uneven distribution of ash/soot
  - Pressure sensors not the best method to determine fill state
- Filter breaking
  - Failure mode for wall flow-through systems
- Long-term real world durability is currently being established

DPF Conclusions

- Currently a successful retro fit technology in both the US and Europe although primarily in 'DPF-friendly' applications i.e. with exhaust temperatures above at least 250C for much of the duty cycle

- Likely to be in common use as an OE fitment by 2007

- Development work through to 2007 will focus on:
  - Improving long term durability
  - Optimizing regeneration procedures (probably active)

Contents

Oxidation Catalysts

- Oxidation cats are a well developed and mature technology
  - reduce HC's and CO
- May be employed to gain engineering margin or as a 'clean up catalyst'
- Will probably be a part of some OE packages, probably in combination with other emission control devices
- Most likely to be applied if HC and/or CO control is an issue – likely to get some PM reduction but minor

Active Lean NOx Catalysts (LNC)

- Also known as HC-SCR
- System requires HC addition (in pipe or in cylinder)
- Catalyst formulated for a specific temperature range
  - Injections only during active temperature window
  - Combination of formulation can extend active window
- Conversion levels are limited
  - 20-30% NOx conversion over FTP cycle reported
  - Thermal management (heating/cooling) would enhance performance
- Potential concern about forming N_2O with platinum based formulations
- Conversion levels too low to be used as primary NOx control solution but:
  - is being developed as a retrofit option (little/no base engine impact – in pipe HC injection)
  - Could be part of a 2007 package to gain engineering margin

Homogeneous Charge Compression Ignition (HCCI)

- HCCI can be considered as a hybrid of SI and CI engine concepts
- HCCI combustion initiates simultaneously at multiple sites within the combustion chamber ⇒ there is little discernible flame propagation
- The largest single attraction of HCCI is that it reduces NOx emissions substantially due to the absence of high temperature regions within the combustion chamber
- The effect of HCCI on unburned hydrocarbon emissions is less clear
- The major development issues are currently
  - HCCI cannot achieve at either very low or high load levels
  - Control and switching between operating modes
  - Developing an improved understanding of the physical and chemical processes that control the combustion phenomena
- The extremely low NOx levels achievable with HCCI are prompting research work but the technology will not be mainstream in time for 2007.

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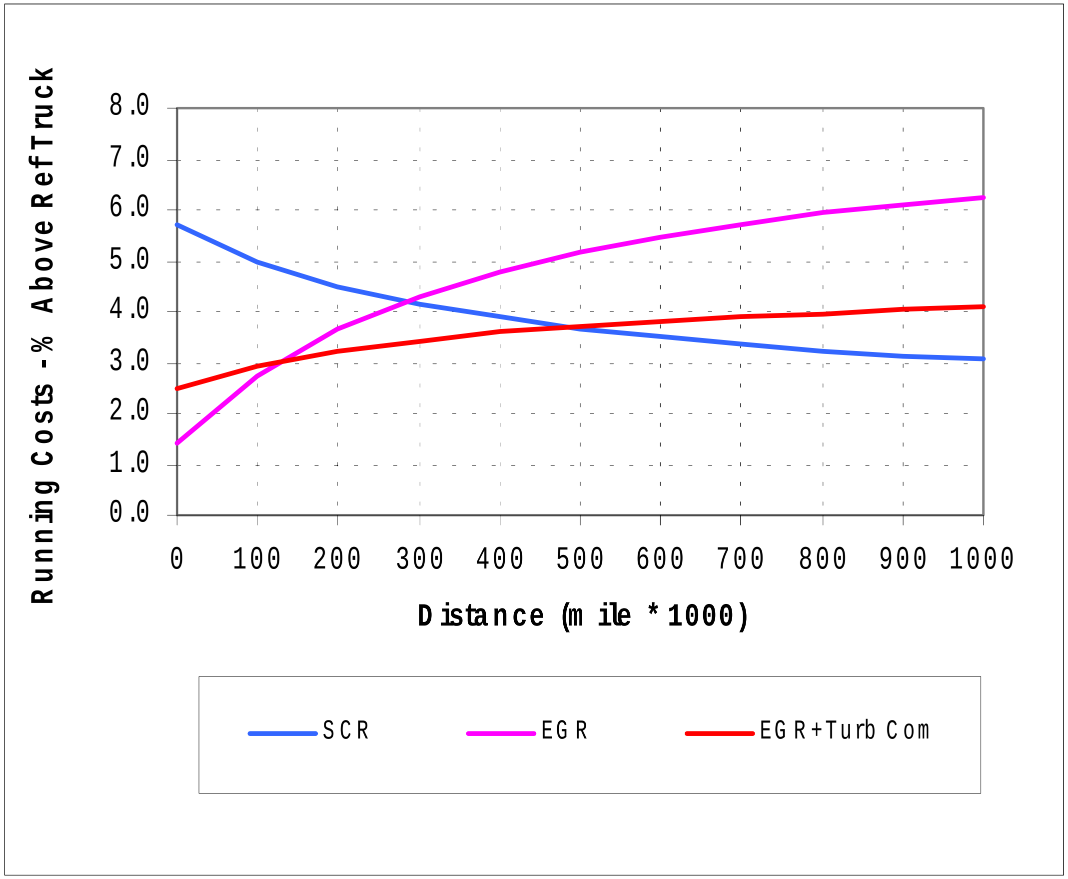
Example of an operating cost analysis of a 2007 compliant truck compared to a 2002 truck (illustrative only)

- Running costs at 0 miles represents capital cost increase over reference truck i.e.

  SCR > (EGT+T'cmpd) > EGR
- In this illustration the running cost of the initially more expensive SCR truck becomes less than the EGR only truck at circa 300k miles and less than the EGR + turbocompound truck at circa 500k miles
- The cost calculation is a function of many different factors such as:
  - Capital cost
  - Diesel fuel & urea costs
  - Maintenance costs



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Production engine developments tend to be evolutionary rather than revolutionary

- In-line 6 cylinder is the dominant engine configuration, accompanied by:
  – 4 cylinder versions of 1 litre/cyl engines
  – V8 and V10 derivatives of 2 litre/cyl for larger displacements
- "Up-sizing" of engines for increased power, not downsizing (as is happening in the light duty markets) due to BMEP limitations enforced by the boost with today's turbomachinery
- Turbocompounding likely to be used by some OEMs for highest power density
  –Already offered by Scania & Volvo and announced for the Iveco Cursor 13
- Examples of evolutionary development of existing engine features would include:
  - Emergence of fracture split con. rods
  - Steel crown, articulated pistons for > 170 bar Pmax
  - Crankcase vent re-circulation added to existing crankcase breathing systems
  - Significant attention to block (ladder bearing frames) and head stiffness for minimum bore distortion under hot-bolted-conditions for lower friction, improved fuel economy and for minimum noise
  - More attention to strategic cooling systems to reduce temperature differential down bore with high coolant jacket with top location, to give improved oil control and lower friction.
  - Attention to water flow in the head to ensure acceptable and uniform flame face temperatures

Increasing specific performance is limited by boosting technology and maximum cylinder pressures

- Current engine ratings lie mostly between 35 and 40hp/litre, with between 20 and 30% torque back up

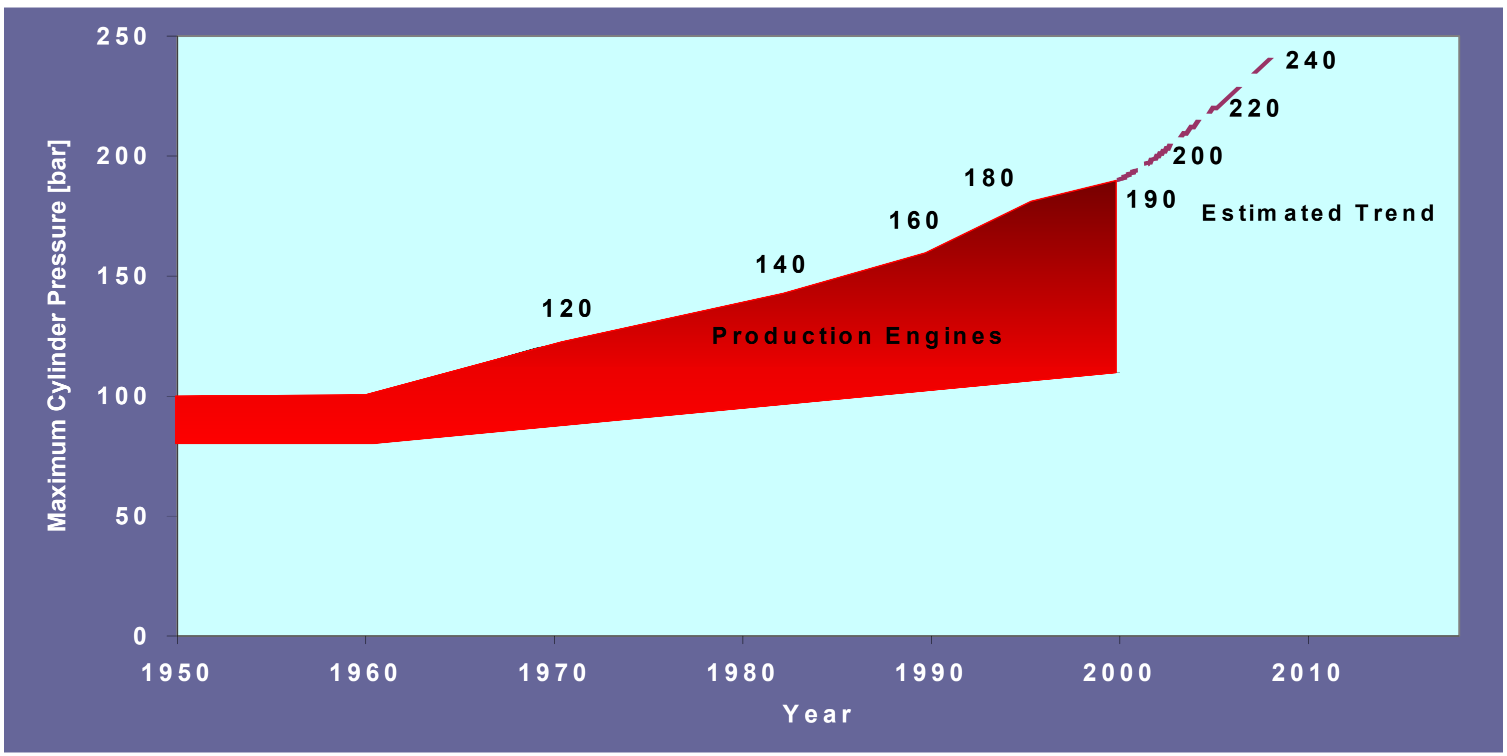
- The limiting technology is typically the boosting system, specifically the capability at peak torque
  - Advances in boosting system will help to alleviate this
  - Maximum cylinder pressures will then become the limiting factor

- The use of SCR aftertreatment would enable higher ratings at lower boost pressures
  - Maximum cylinder pressures could then also become the limiting factor because of advanced injection timings

- Most manufacturers will be constrained by existing engine structures
  - Pmax will be increased within limits of major components (with minor redesign in feasible)
  - New engine designs will likely feature significantly high Pmax capability

It is especially important to design for optimum peak cylinder pressure with a view to future potential

- Peak cylinder pressures are generally between 160 and 200 bar today
  - –Maximum cylinder pressures will increase to as much as 240 bar by 2012
  - –This will be enabled in part by the introduction of CGI cylinder blocks
  - –Longer term research is looking at pressures of up to 300 bar



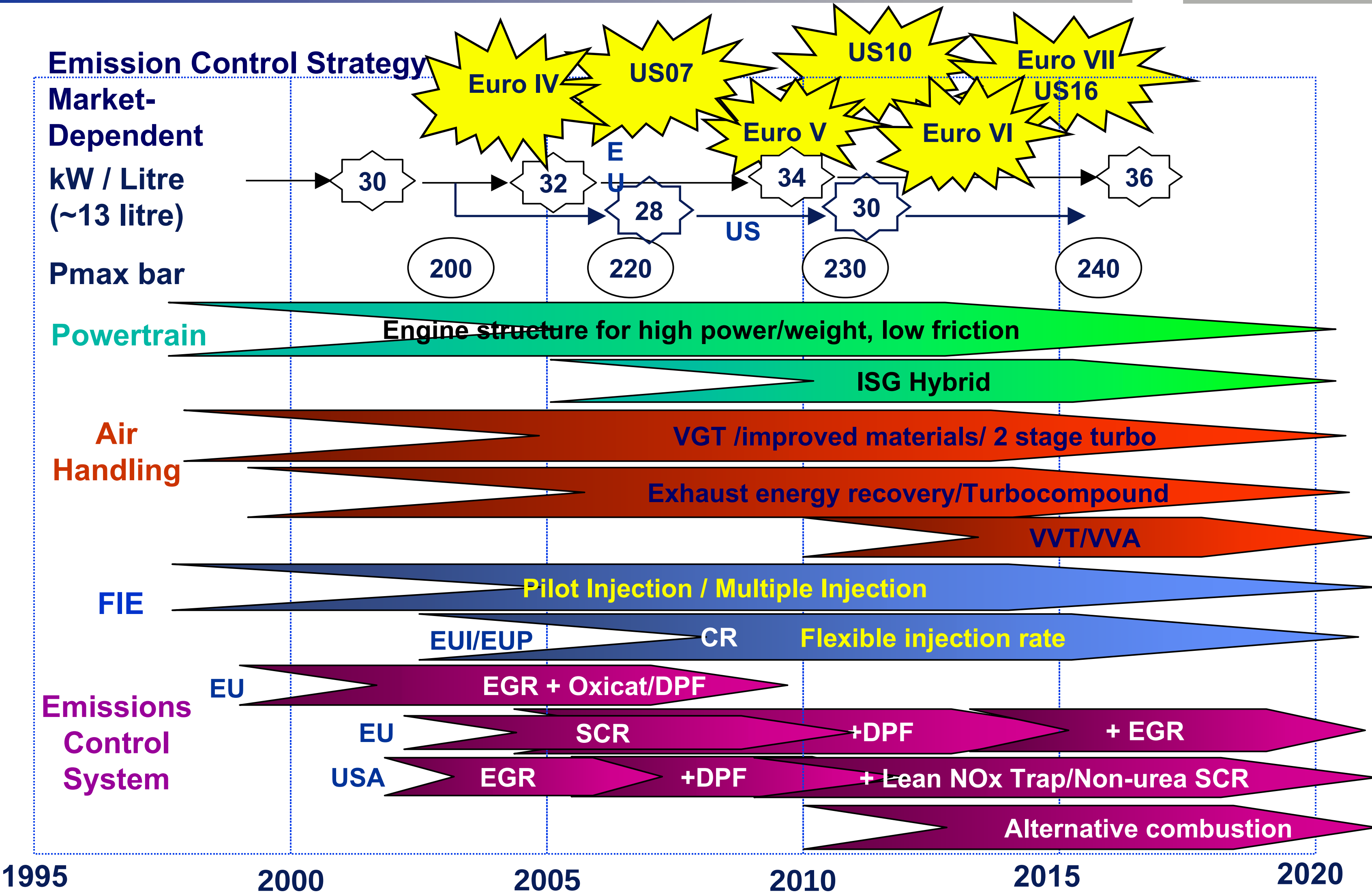
What's on the horizon for engine developments for the next 5 years?

- VVA/VVT – multiple benefits including thermal management of aftertreatment, internal EGR, exhaust braking, HCCI control etc.

- Continual improvements in turbomachinery
  - Electric boosting
  - 2-stage (Caterpillar already using)/Turbocompounding
  - Titanium compressor wheels
  - Variable geometry compressor (increase map width)

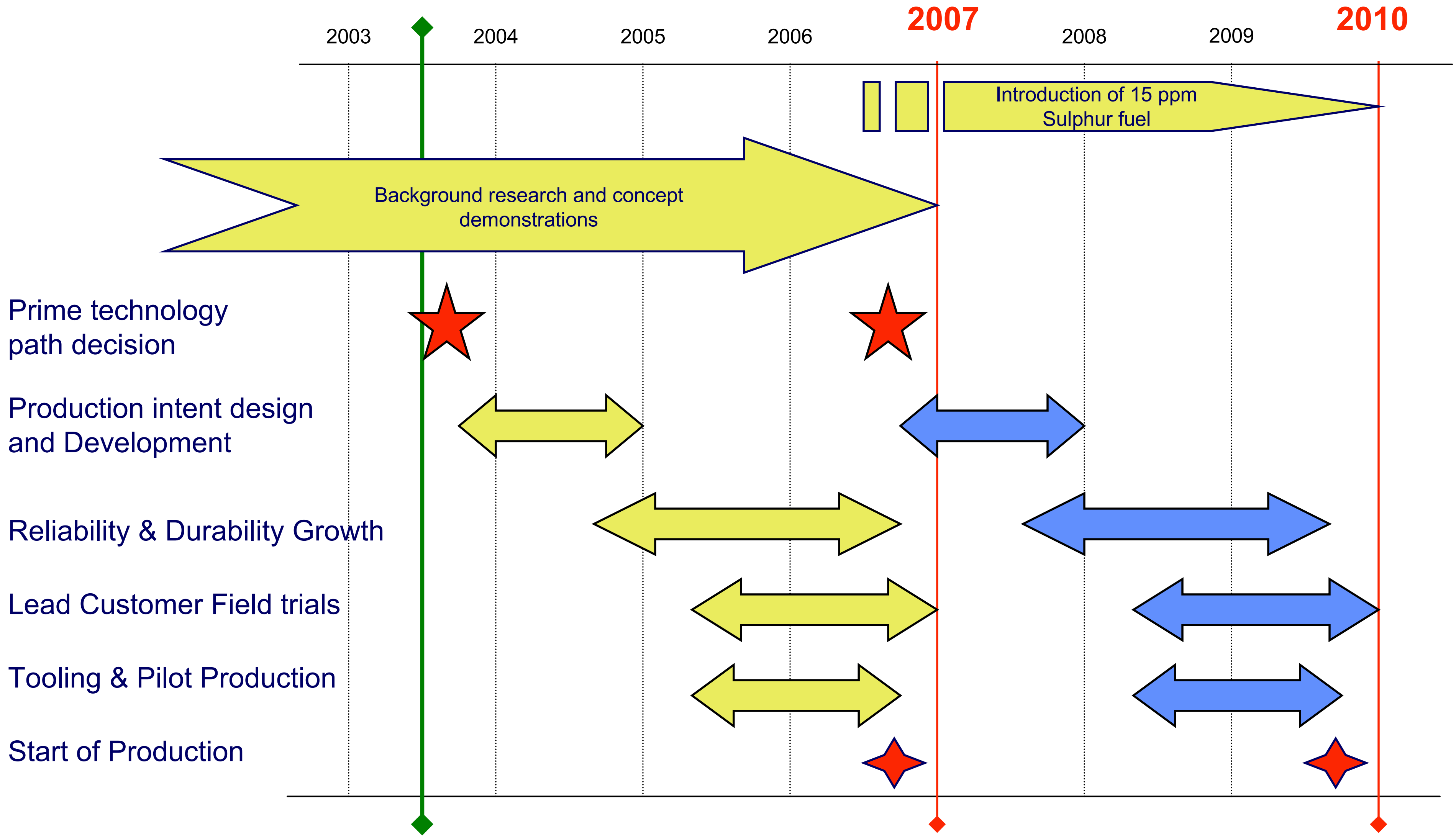
- Fuel injection
  - Continued increase in maximum injection pressure
  - Increasing control flexibility (multiple injections at varying pressures)
  - Likely gradual trend to common rail

The trend of increasing specific performance is constrained by emissions legislation and it is diverging between the US & Europe



Contents

High Level Program Schedule – 2007/2010



2007/2010 Product Planning

- The short time frame between 2007 and 2010 means that OEMs will have to make decisions on their prime 2010 technology path before the 2007 engines are in full production

- It is therefore important for OEM's to consider their long term path to 2010 as a part of the technology selection process for 2007

Contents

- ❑ Introduction/Background
- ❑ Summary of main points of the 2007/2010 legislation
- ❑ Discussion of main technical options
  - –Higher EGR rates
  - –Lean NOx traps
  - –Selective Catalytic Reduction
  - –Diesel Particulate Filters
  - –Other 2007/2010 options
- ❑ Cost Analysis
- ❑ Base Engine Design Changes
- ❑ Development timetables
- ❑ **Summary**

Summary

- Meeting 2007 PM emissions levels will require the use of DPFs. Although there is development work still to be completed, the technology looks well down a path to maturity
- 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 these 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 is however key and an early industry-wide consensus and commitment would be needed in order to make this a practical reality for 2007
  - 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.)

- 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

Contact information

Graham B. Weller

Ricardo Inc.

7850 Grant Street

Burr Ridge, IL. 60527

Tel: (630) 789 0003

graham.weller@ricardo.com