Heavy-Duty Diesel Engine Trends to Meet Future Emissions Standards (Euro VI)

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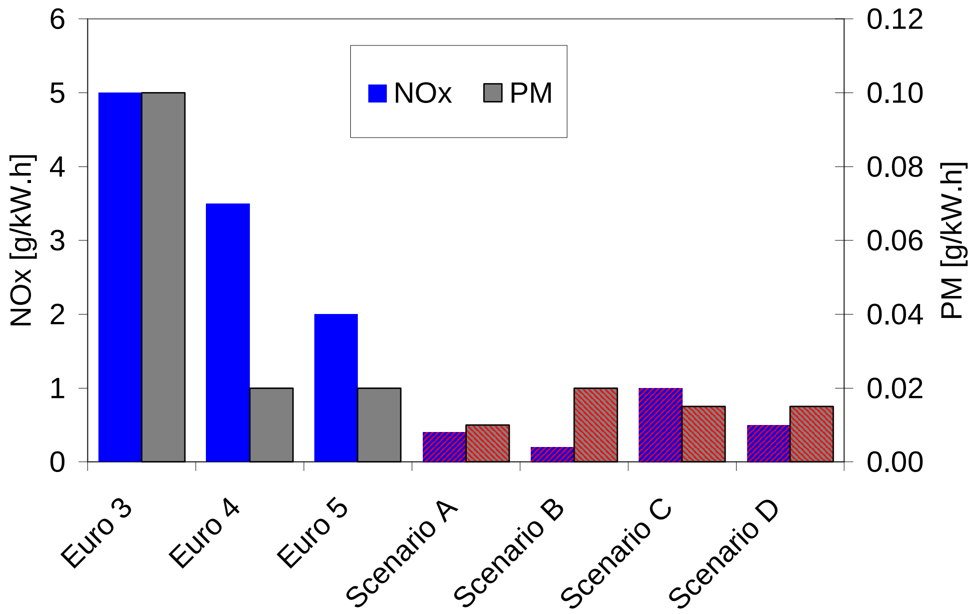
Contents

Exhaust Emissions Scenarios for Euro VI: Significant reductions in NOx and PM are expected

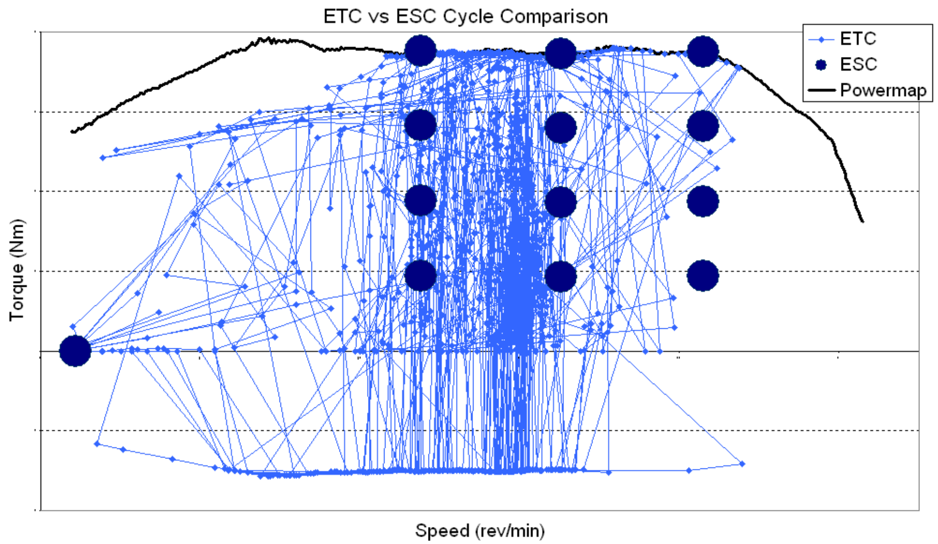
- Euro IV and Euro V exhaust emissions limits have been met by development of engine technologies, to minimise dependence on aftertreatment
- July-Sept., 2007: European Commission undertook public consultation regarding Euro VI limits
- Limits likely to be set at a level to persuade manufacturers to use available technologies:
  - NOx: combination of cooled EGR and SCR aftertreatment
  - PM: Diesel particulate filters
- Likely introduction date: 2013~2014
- Other issues:
  - Test procedures: WHTC offset?
  - Particle Number Limit?
  - Ammonia limit (covered by OBD)?
  - Conflict of fuel consumption penalty at very low NOx levels

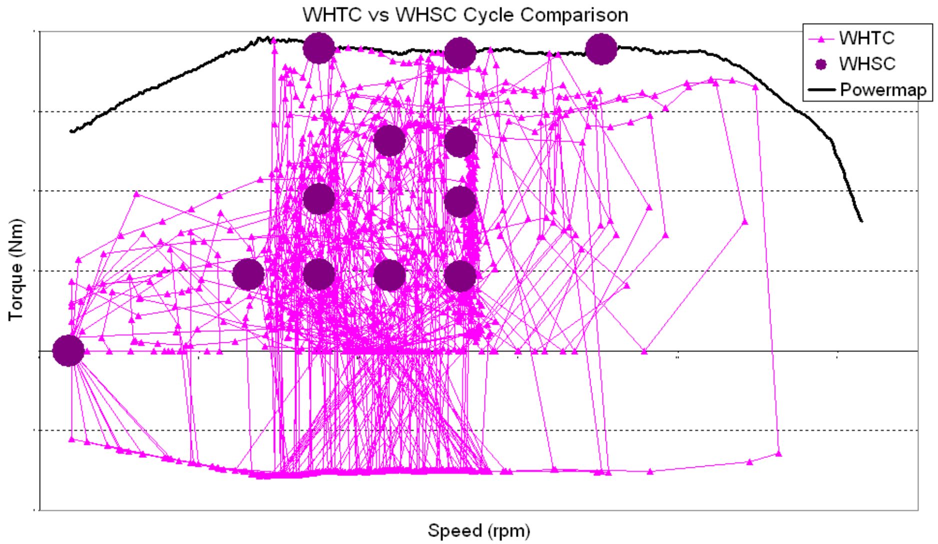


	Scenario A	Scenario B	Scenario C	Scenario D
CO g/kW.h	4.0	4.0	4.0	4.0
THC g/kW.h	0.16	0.55	0.55	0.55
NOx g/kW.h	0.4	0.2	1.0	0.5
PM g/kW.h	0.01	0.02	0.015	0.015

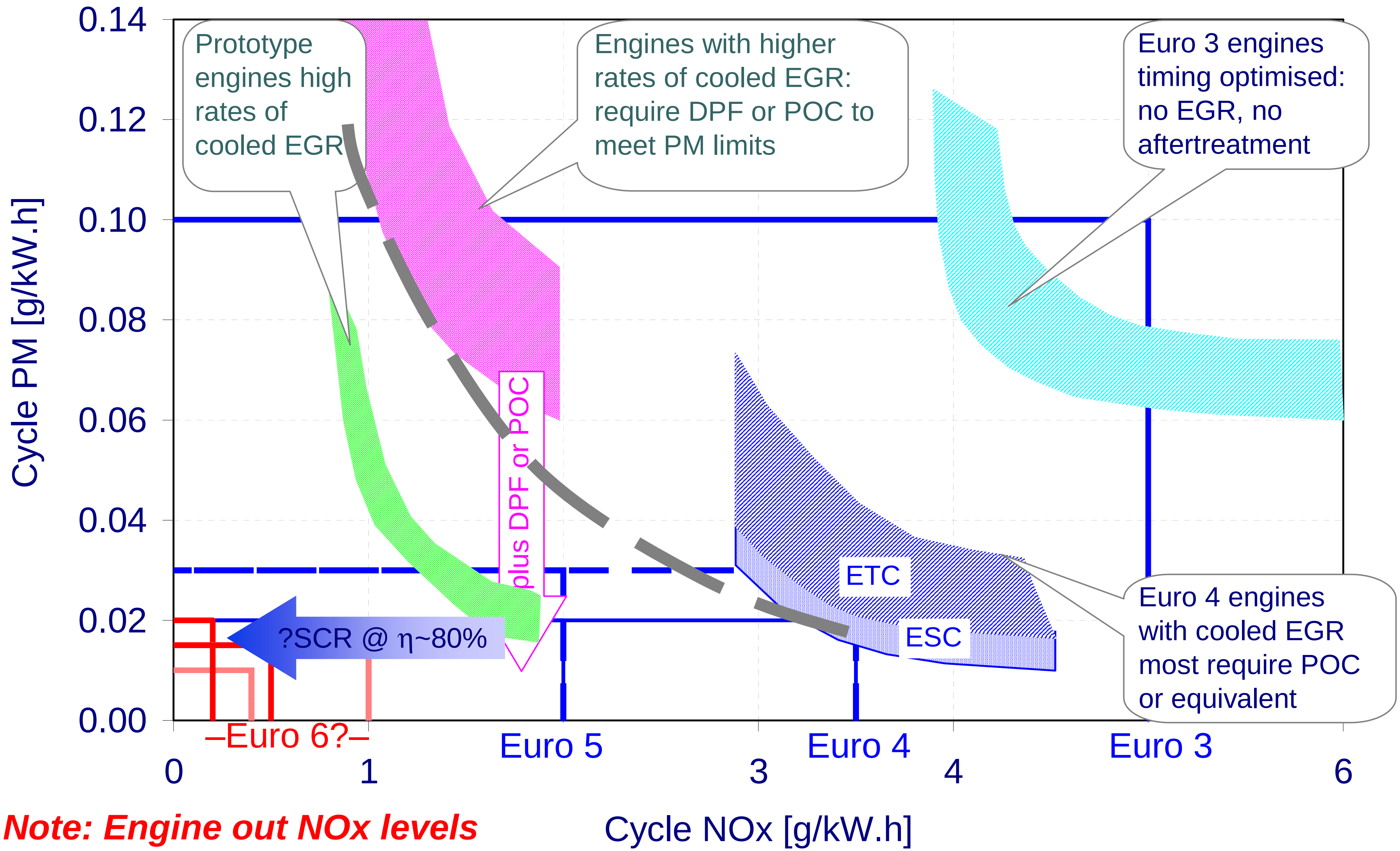
Test Procedures for Euro VI
World-wide Harmonised procedures may be adopted

- Current procedures (Euro III ~ Euro V)
  - ESC: European Steady-state Cycle
  - ETC: European Transient Cycle
  - Both tests are "hot start"
- Replacement of current procedures with Worldwide Harmonised Tests (WHTC & WHSC) is under discussion
- WHSC test includes full load modes – emissions controls must be effective at full load with high exhaust temperatures
- WHTC Cycle will include a cold start cycle
  - weighting: 10% cold; 90% hot
  - soak time before hot start not fully defined options are in the range 5~20 minutes
- WHTC test has lower average load factor on the engine, hence exhaust temperatures will be lower



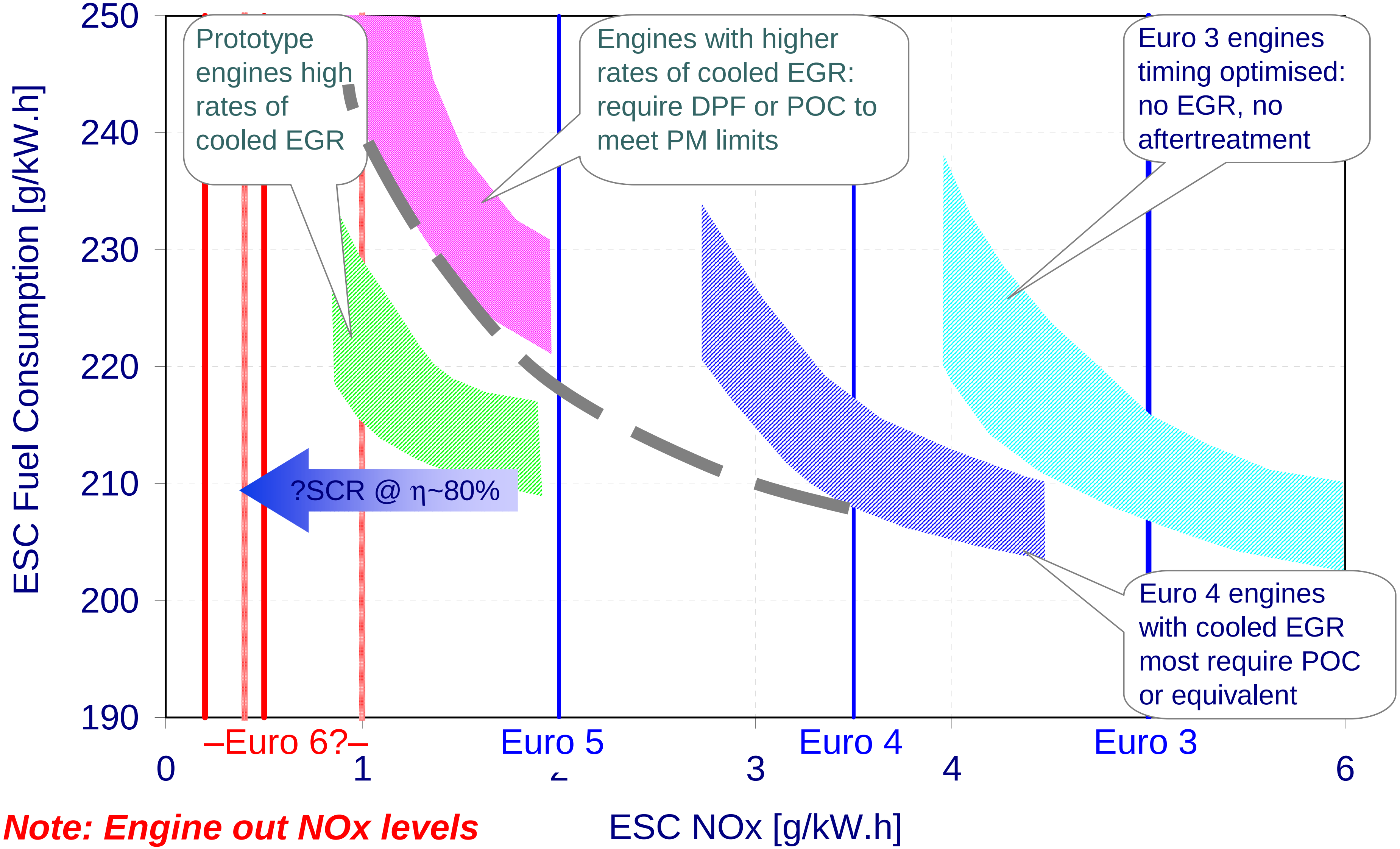


NOx-Particulate Trade-offs at Successive Emissions Levels
Euro VI scenarios will require additional technology



Note: Engine out NOx levels

NOx-Fuel Consumption Trade-offs at Successive Emissions Levels
Concern that very low NOx levels affects fuel consumption



Note: Engine out NOx levels

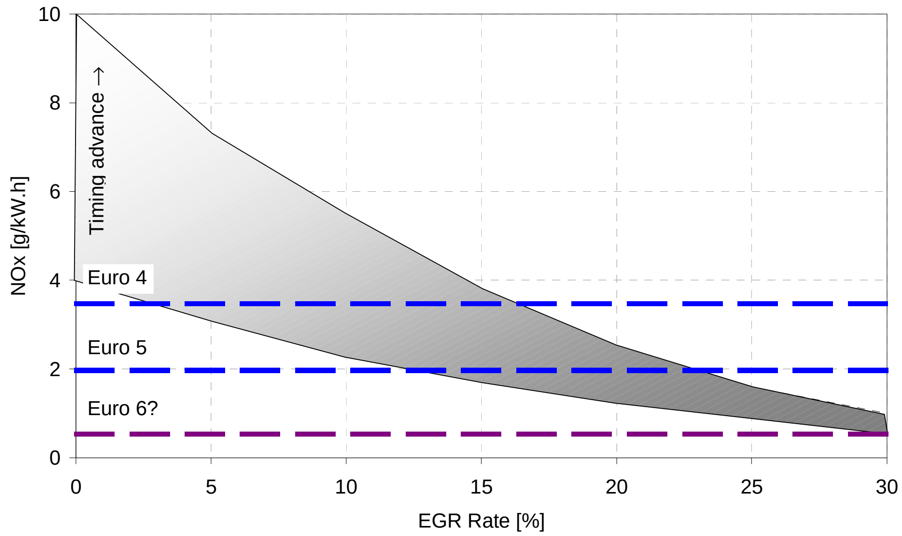
NOx Emissions Reduction Engine Out
Very low NOx levels achievable by combining EGR and SCR

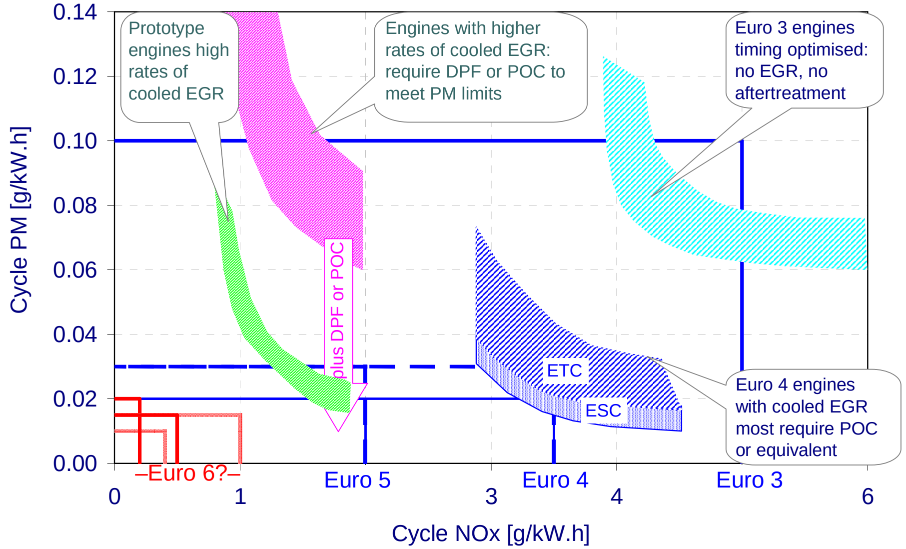
4.5~5.0 g/kWh NOx (Euro III):
- Achievable by fuel injection timing retard
- EGR not required

3.0~3.5 g/kW.h NOx (Euro IV):
- Can be achieved with timing and combustion optimisation
- Moderate rates of cooled EGR
- (10~18% at full load)

1.0~1.5 g/kW.h NOx (sub-Euro V):
- High rates of cooled EGR (~30% at full load) over a wide speed range
- Demand for adequate air-fuel ratio and competitive power and torque

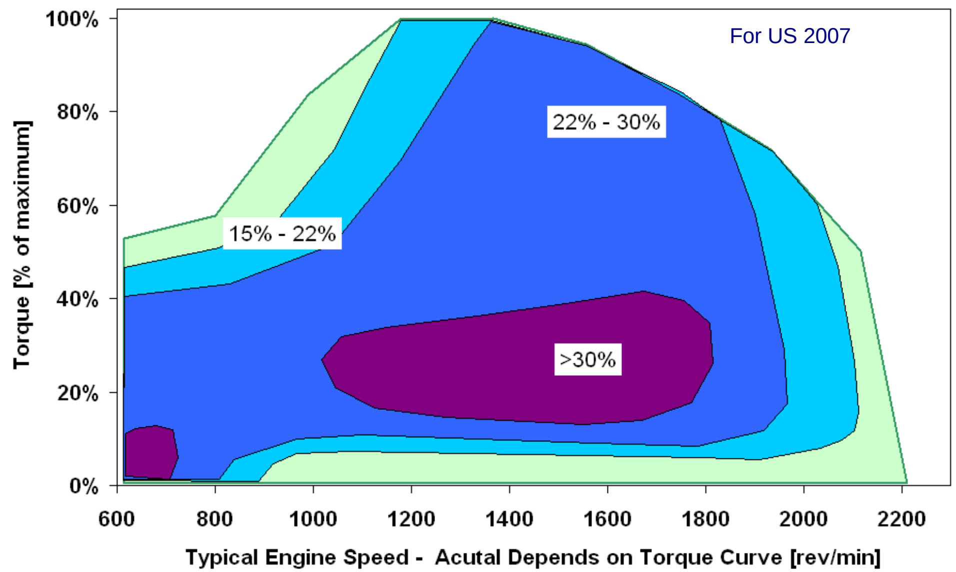
<0.4 g/kW.h NOx (Euro VI?):
- Achievable at lighter part-load conditions (<10 bar BMEP) using highly pre-mixed cool combustion
- Further work required to extend to full load (~20 bar BMEP), including variable compression ratio, and cylinder pressure based electronic control

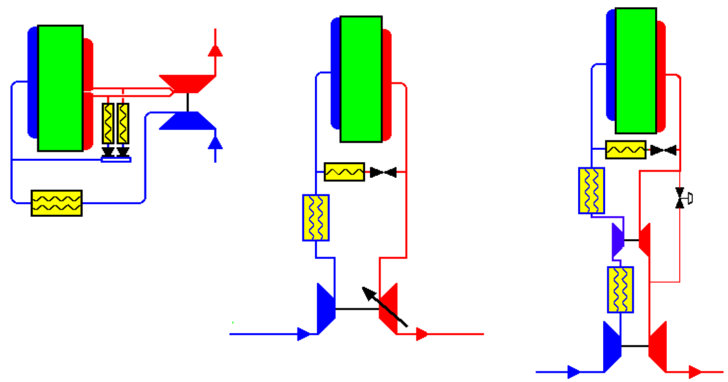




NOx Reduction by Cooled EGR for Heavy Duty Diesel Engines
Cooled EGR unlikely to be sufficient for Euro VI

- Cooled EGR is very effective for NOx reduction
- EGR must be used at full load on Heavy Duty engines to meet requirements of the emissions certification test cycles
- Typical full load EGR rates:
  - Euro IV (~3 g/kW.h): 10% ~ 18%
  - Euro V (~2 g/kW.h): 15% ~ 25%
  - (~1 g./kW.h): 27% ~ 33%
- Minimum cycle NOx levels achievable with EGR currently ~0.9 g/kW.h, using conventional combustion systems and fuels
- Additional NOx reduction technology required for Euro VI, if less than ~1.0 g/kW.h):
  - SCR Aftertreatment
  - Or Highly Pre-mixed Cool Combustion, but this is not likely to be production feasible before 2014 – effect on fuel consumption to be determined





PM Emissions Reduction Engine Out
Improved air-fuel mixing and fuel atomisation key to low PM

Combustion System

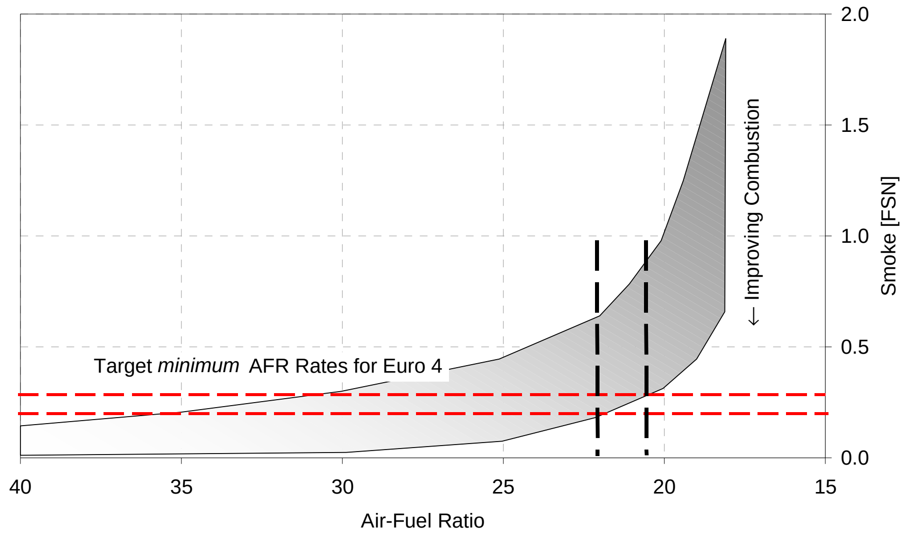
- Inlet swirl ratio – matched to fuel system & nozzle geometry
- Piston bowl – re-entrant piston bowls for best mixing at retarded timings
- Nozzle geometry – interactions with bowl shape and swirl ratio

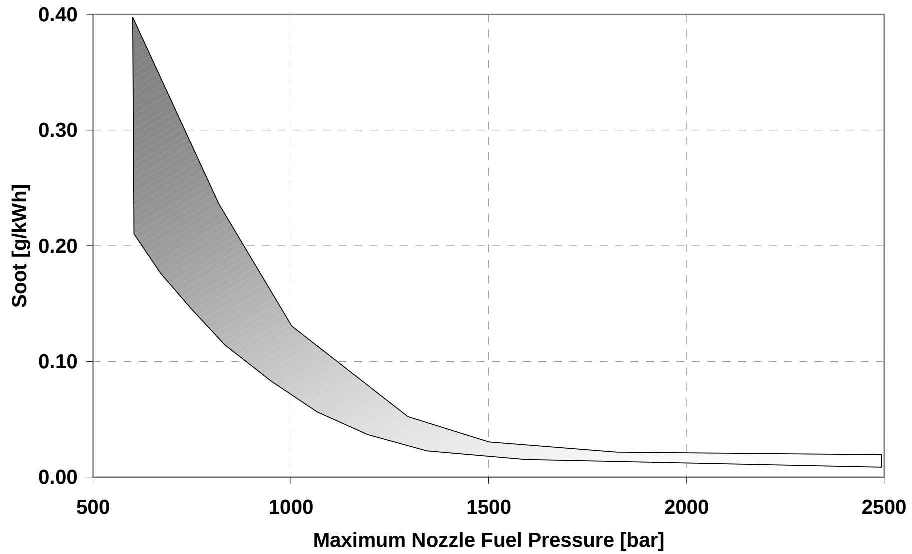
Boosting System:

- Adequate air-fuel ratio, especially with high rates of EGR
- Air-air aftercooling
- Trends toward variable geometry turbochargers and two-stage turbochargers

Fuel Injection System:

- Improved fuel atomisation – increased fuel pressures
- Improved timing / phasing of fuel injection – electronically control, multiple injection
- Optimised pressure – according to engine operating conditions





Fuel Injection System Trends
Towards higher fuel pressures and multiple injections per cycle

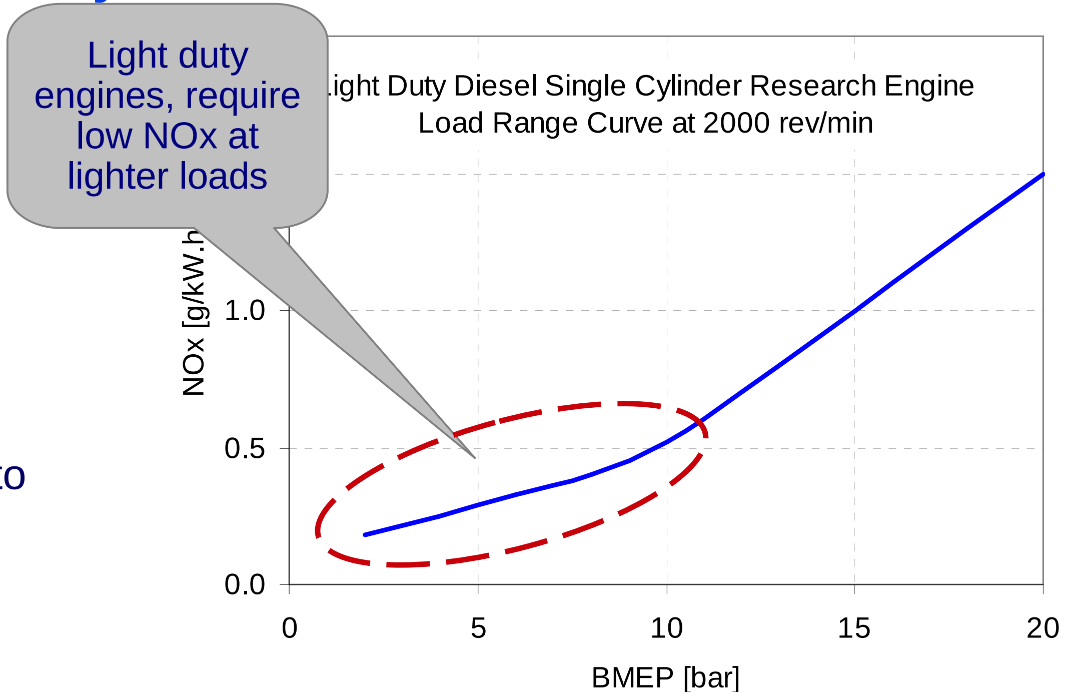
- **Electronic Unit injectors:**
  - Highest pressure capability of available Fuel Injection Systems, since introduction in Europe ~1993 (Volvo D12 fitted with Delphi EUIs)
  - Initial EUI systems had maximum fuel dependent on engine speed and fuelling level and single injection per cycle
  - Current production Delphi E3 has capability of **2250~2500 bar**
    - Two solenoid valves enhance pressure capability at part load and speed, multiple injections per cycle feasible

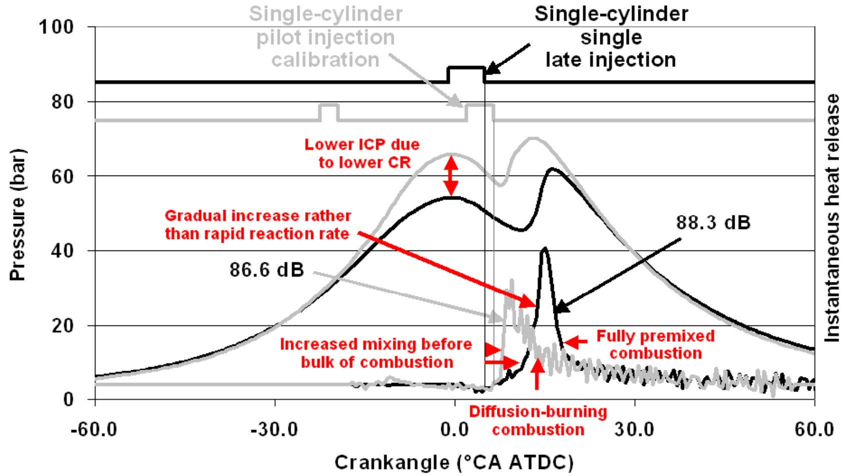
- **Common Rail for Heavy Duty Applications:**
  - Greater flexibility over fuel injection timing, pressure and multiple injection than other Fuel Injection Systems
  - First introduced in Japan (Denso). First European HD engines with Bosch Common Rail: MAN, Renault VI circa. 2002
  - Currently (Euro IV): up to **1600 bar (HD), 1800 bar (MD)** available in production for Heavy Duty applications over a wide speed and load range
  - Scania/Cummins **XPI**: for Euro V engines capable of **2400 bar** (without intensifier)

- **Future Trends**
  - Major FIE suppliers likely to follow trend towards Common Rail FIE for most flexibility over injection timing, rate, pressure and number of injections. Development of systems with pressures up to 2400 bar planned

Low NOx Combustion – Highly Pre-Mixed Cool Combustion
Light Duty experience shows way to very low NOx

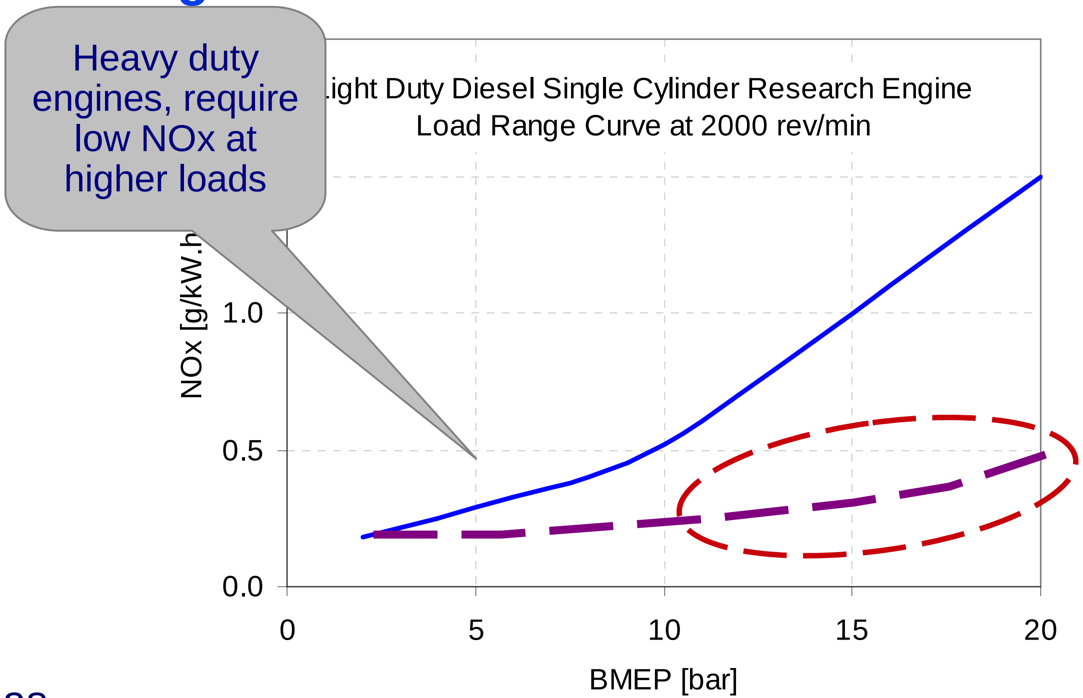
- Engine out specific NOx levels as low as 0.2 g/kW.h have been demonstrated on a single cylinder research engine:
- Key technologies:
  - Thorough air-fuel mixing
    - high fuel pressures (atomisation)
    - moderate swirl and bowl (mixing)
  - Controlled compression temperatures to maximise mixing time:
    - Reduced compression ratio
    - Modulated aftercooler
    - Modulated EGR cooler
  - Controlled rate of combustion:
    - High EGR rates
    - Controlled boosting system (low O_2)
- Ricardo Highly Pre-mixed Combustion Concept (HPCC) uses fuel injection near TDC, to avoid potential problems of high HC and CO emissions experienced with HCCI concepts

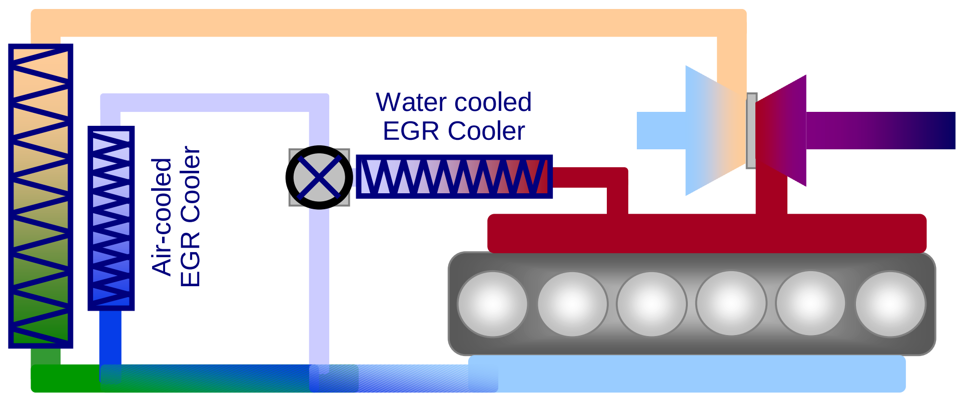




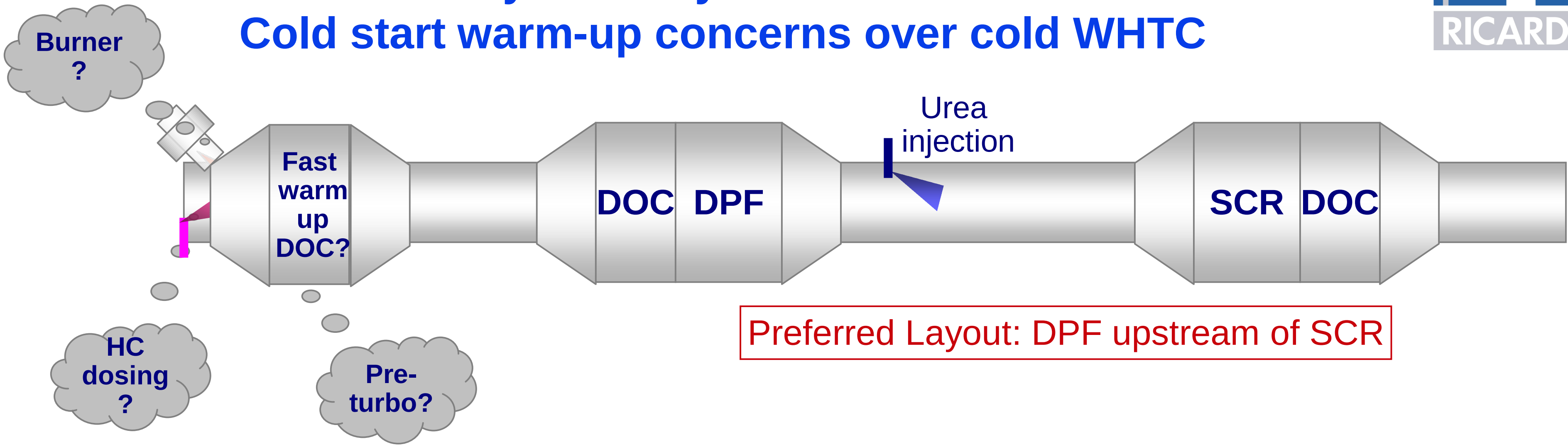
Low NOx Combustion – Heavy Duty engines will require additional technology to enable cool combustion at higher loads

- To extend HPCC to higher loads requires additional technologies:
  - Control of end of compression temperatures by:
    - Variable valve actuation (VVA)
    - Variable compression ratio (VCR)
    - Inlet charge (air & EGR) temperature control
- VVA & VCR require complex mechanical systems – production feasibility to be established
- The need for lower charge temperatures has lead to the development of 2-stage EGR cooling
- At higher loads small differences in in-cylinder conditions have a significant ignition timing and rate of heat release
  - Cylinder-pressure based monitoring and control will be essential, to ensure combustion equalised across all cylinders

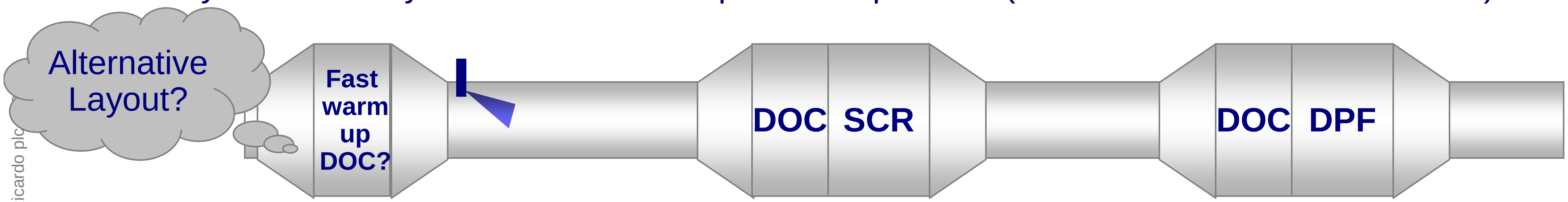




Exhaust Aftertreatment System Layout:
Cold start warm-up concerns over cold WHTC

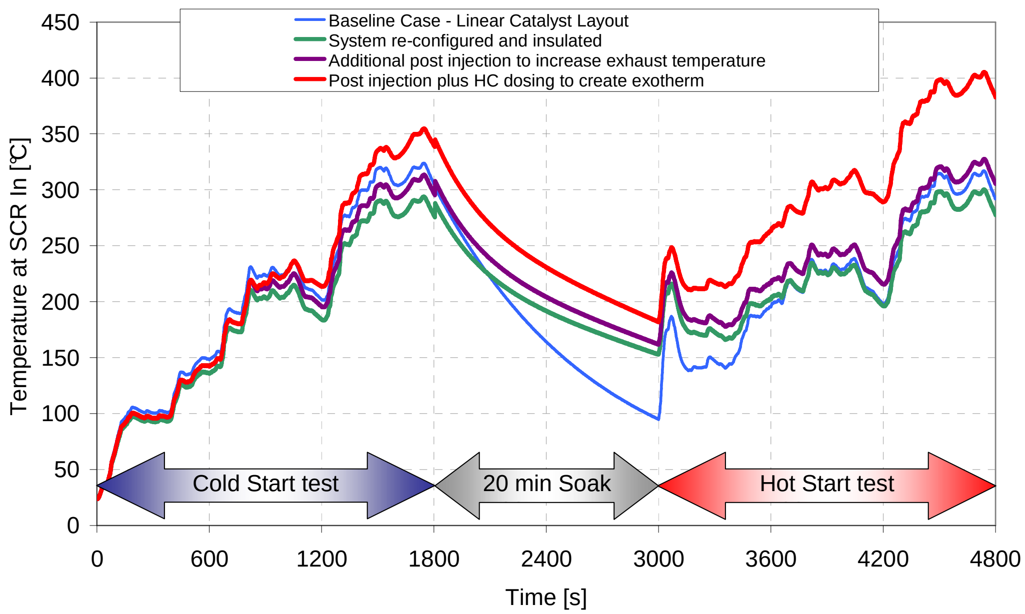


- DPF upstream of the SCR is most common:
  - Energy required for active regeneration of DPF minimised
  - NO_2 available for passive regeneration in the DPF
  - SCR does not tolerate high engine out exhaust temperatures (during regeneration)
- Downstream SCR:
  - Slow temperature increase after cold start limits catalyst effectiveness – concerns for some certification tests
  - System not very effective in low temperature operation (such as buses and refuse carts)



Test procedures which include a cold start cycle require careful thermal management of the catalyst system

- Thermal management of the catalyst system can be achieved using a range of measures including:
  - System layout to minimise heat losses (insulation can slow warm up)
  - Throttling and/or EGR (must avoid misfire)
  - Post injection (late combustion raises exhaust temperature)
  - HC dosing (exotherm over DOC)
  - Aftercooler and EGR cooler bypasses



- Many of the modifications to improve warm up will increase fuel consumption because of the heat energy demand
- The use of exhaust burners has been considered, but there are concerns about reliability and the fuel consumption of these devices
- The technologies needed to provide rapid warm up of catalysts are under development to meet the US'2010 emissions regulations

Summary of Technology Requirements for Heady Duty Diesel Engine Emissions Reduction: Euro IV through Euro VI

	Euro IV	Euro V	Euro VI
NOx Reduction Technologies	SCR ***OR*** Cooled EGR	SCR ***OR*** Cooled EGR	SCR ***PLUS*** Cooled EGR
PM Reduction Technologies	Combustion & FIE System Optimisation (POC on some engines with EGR; DPF only if customer requirement)	Combustion & FIE System Optimisation (POC or DPF on some engines with EGR, or if customer requirement)	Combustion & FIE System Optimisation ***PLUS*** DPF
Emerging Technologies	OBD requirements	2-Stage EGR Coolers	Potential alternative HPCC Cool Combustion (HP modulated-FIE? VVA? VCR?)?

Summary

- Typical Euro VI Heavy Duty Diesel Engines are likely to use:
  - Cooled EGR plus SCR and DPF
- Exhaust emissions regulations have traditionally been met by modifying and improving the engine technologies, specifically: combustion system, boosting system, fuel injection system, and (where applicable) the EGR system
- SCR systems have been introduced to reduce NOx to Euro IV and Euro V levels:
  - Conversion efficiencies of 75%~85% are feasible over current test procedures
  - Euro IV/V engines with SCR do not use EGR
  - Combined SCR plus cooled EGR would enable Euro VI NOx levels to be achieved
- Cooled EGR can be used to meet Euro IV and Euro V NOx levels, but tends to increase PM
  - Low PM can be achieved by adding a Particulate Oxidation Catalyst or DPF
  - Alternative is re-optimised combustion and EGR systems with improved FIE
- Very low engine-out NOx would require sophisticated control of the combustion process to ameliorate peak temperatures and pressures in the cylinder. This is likely to require additional engine technologies, such as variable cooling, variable valve actuation and/or variable compression ratio systems, and is unlikely to be production feasible before 2014
- DPFs have not been widely used for Euro IV and Euro V
  - Euro VI levels likely to be set to force DPFs
- A change to the World-Harmonised test procedures will require thermal management of the exhaust gas to ensure that SCR systems rapidly become effective after cold starting. If WHTC is adopted the limit values will require an offset from ETC numbers.