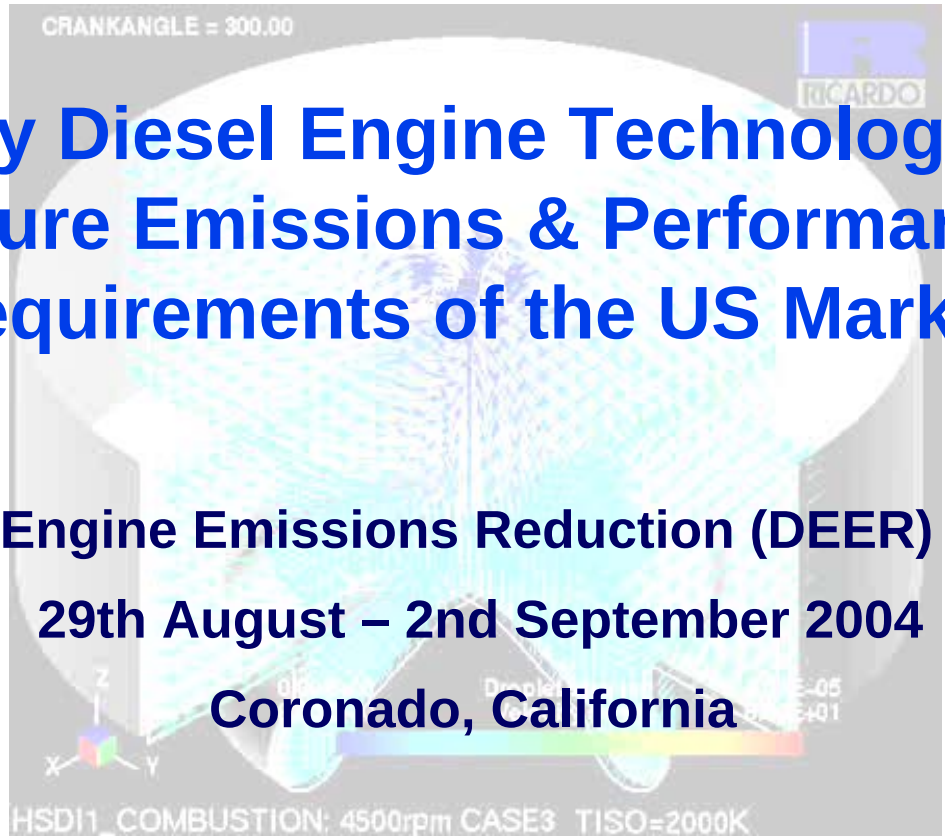


Light Duty Diesel Engine Technology to Meet Future Emissions & Performance Requirements of the US Market

10th Diesel Engine Emissions Reduction (DEER) Conference

29th August – 2nd September 2004

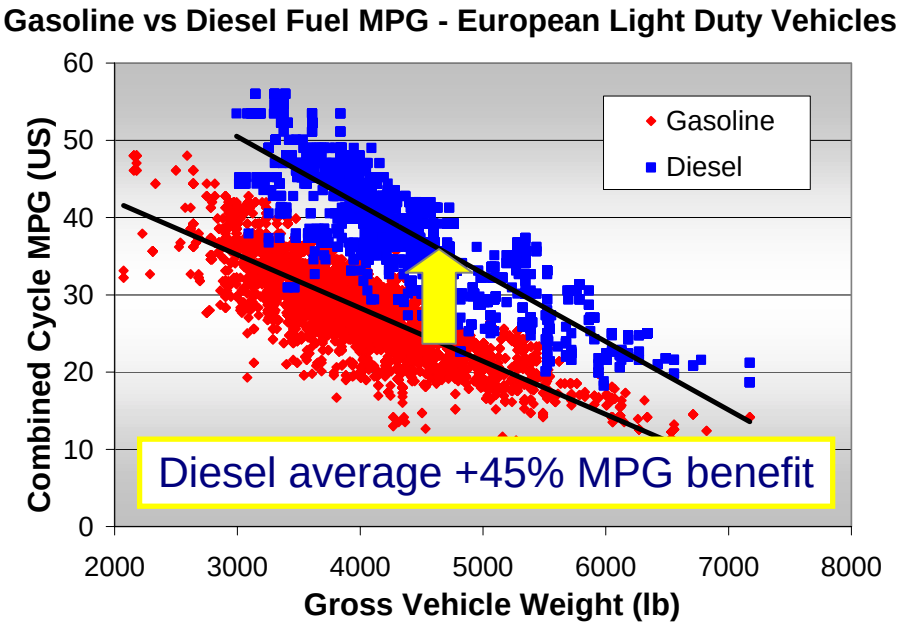
Coronado, California

A M Greaney, Ricardo, Inc. AMGreaney@ricardo.com

Several challenges must be met to exploit the fuel economy & performance benefits of light duty diesel in the US market

Opportunities

- **CAFE** improvement & **CO_2** Reduction
- **Vehicle range**
- **Diesel appeal** of torque performance
- **Incremental market share** for product leaders



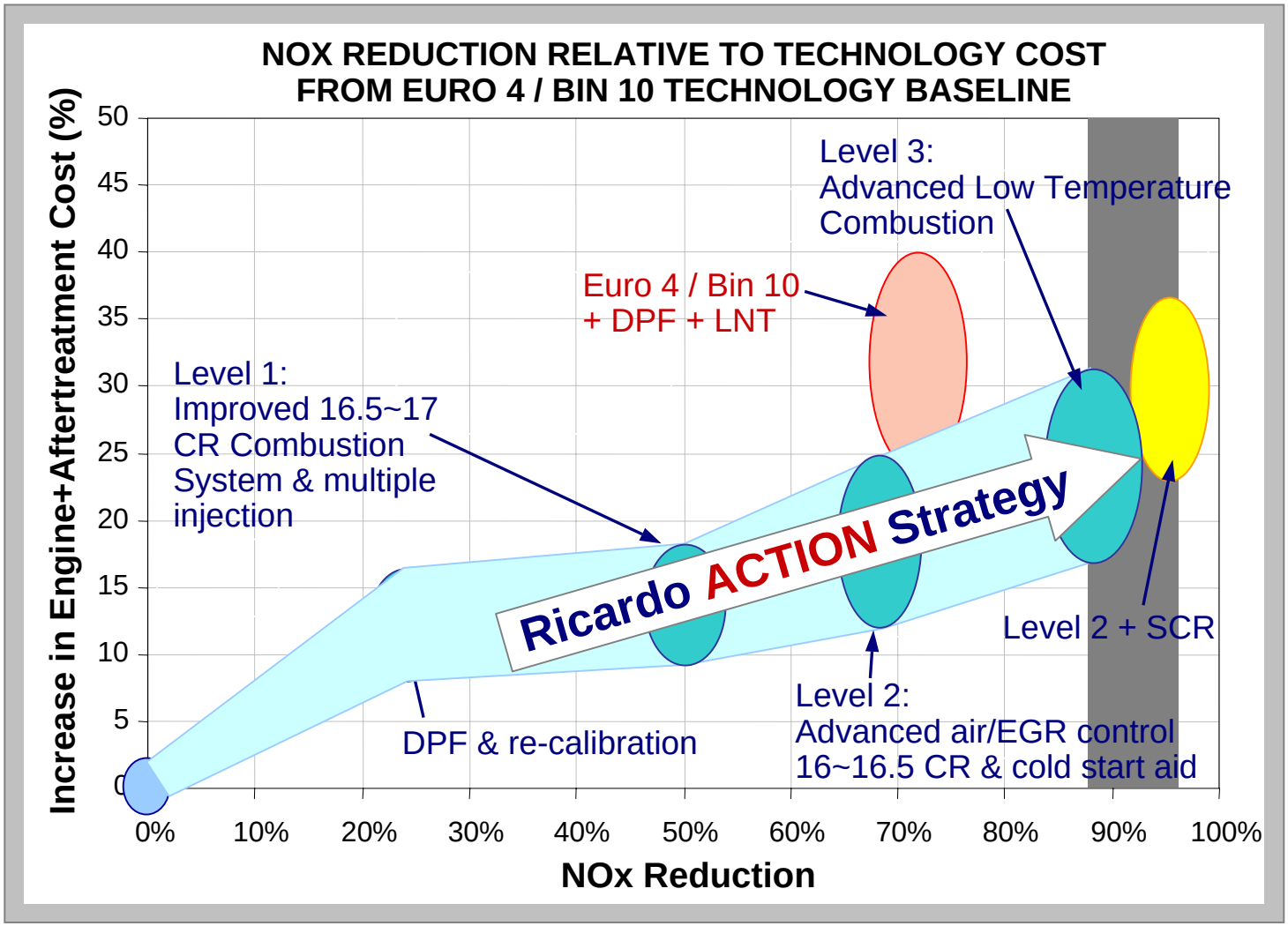
Challenges

- Meeting Tier 2 Bin 5 **Emission** with **Robustness** & **Durability**
- Competitive **Launch Performance** & **Refinement** vs premium gasoline V-engines
- US **market acceptance** of light duty diesel products
- Widespread availability of **low sulfur fuel**

Need to meet all product attribute requirements within a **Viable Business Case**

Market issues addressed by demand if good diesel products offered

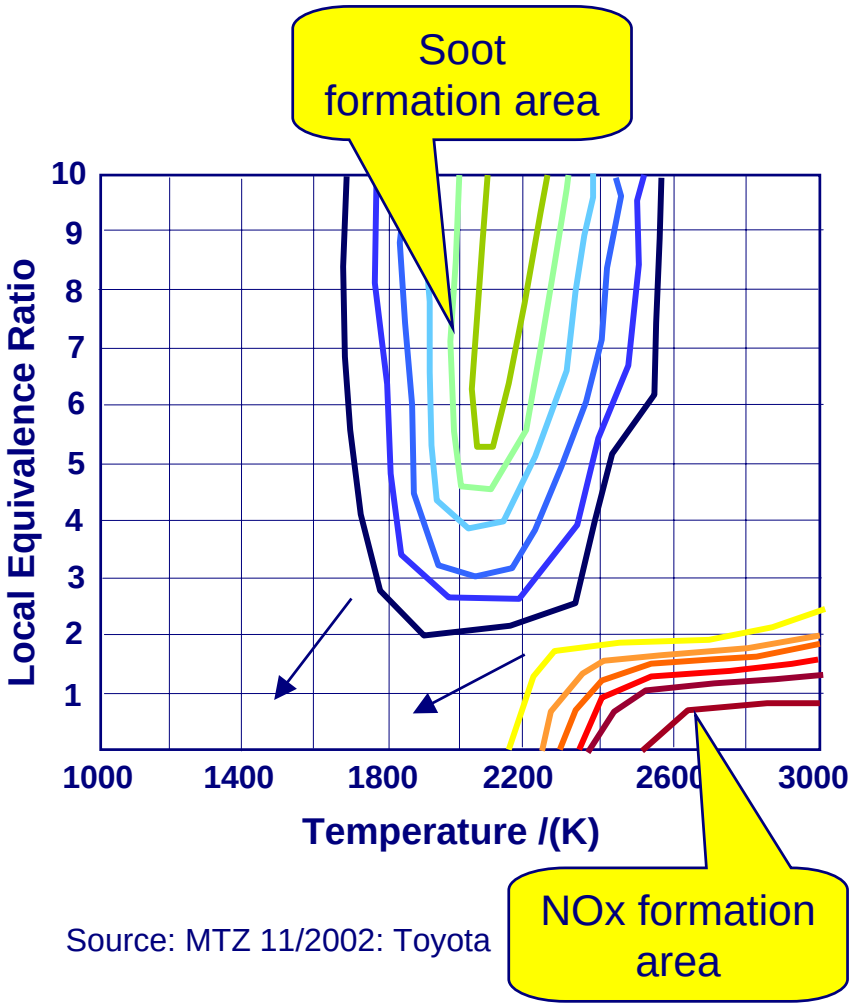
Engine technologies to reduce NOx at source and minimize NOx aftertreatment offers the most viable business case



ACTION: Advanced Combustion Technology for Improved engine-Out NOx

- Cost/benefit estimates for 100,000~150,000 units per annum
- Base cost assumes $3000~$3500 V6 variable cost and Euro 4 / Bin10 capability

The route to reduced engine-out emissions is highly pre-mixed and lower temperature combustion



Source: MTZ 11/2002: Toyota

APPROACH

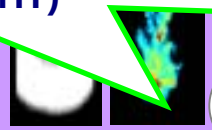
- IMPROVED AIR/FUEL MIXING
- INCREASED IGNITION DELAY
- INCREASED EGR RATES AND TEMPERATURE MANAGEMENT
- IMPROVED AIR SYSTEM EFFICIENCY
- COMBUSTION AND TRANSIENT CONTROL

The ACTION strategy integrates engine technologies to deliver low engine-out emissions with performance, refinement & fuel economy

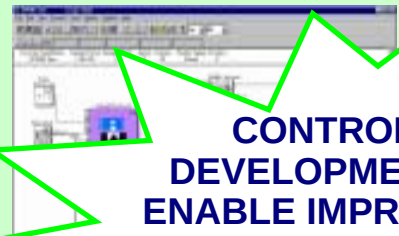
Low Compression Ratio Combustion System Design

LOW CR ⇒PERFORMANCE WITH LOW PMAX (LOW COST & WEIGHT)

Fuel Injection Technology



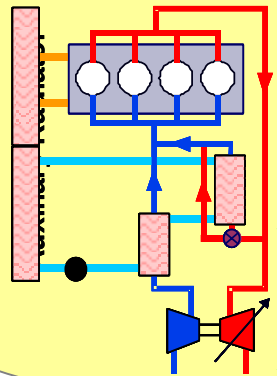
Closed-Loop Model Based Control Developments

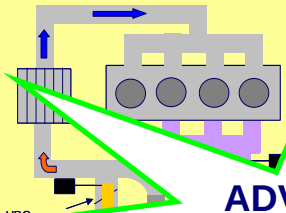


CONTROL DEVELOPMENTS ENABLE IMPROVED REFINEMENT & REDUCED COMPONENT COSTS

LOW ENGINE-OUT NOx

EGR & Boosting System Developments



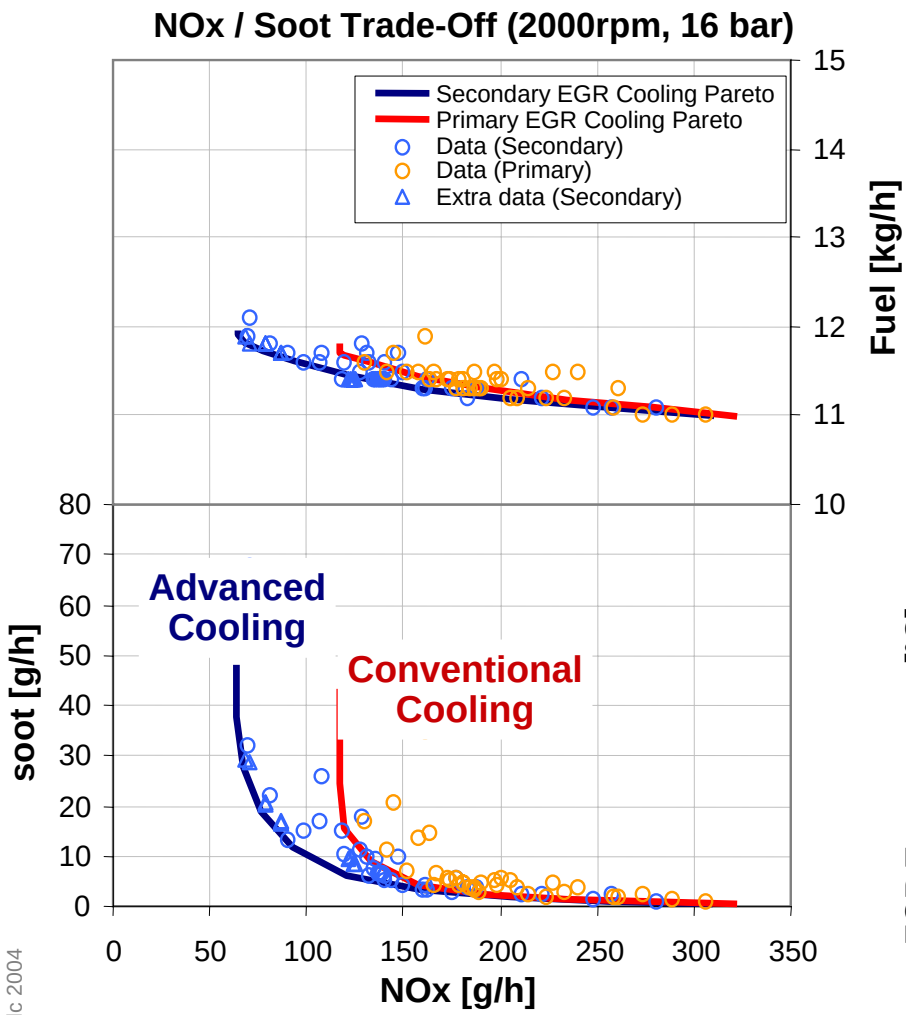


ADVANCED BOOST SYSTEMS ⇒PERFORMANCE & ECONOMY BENEFITS

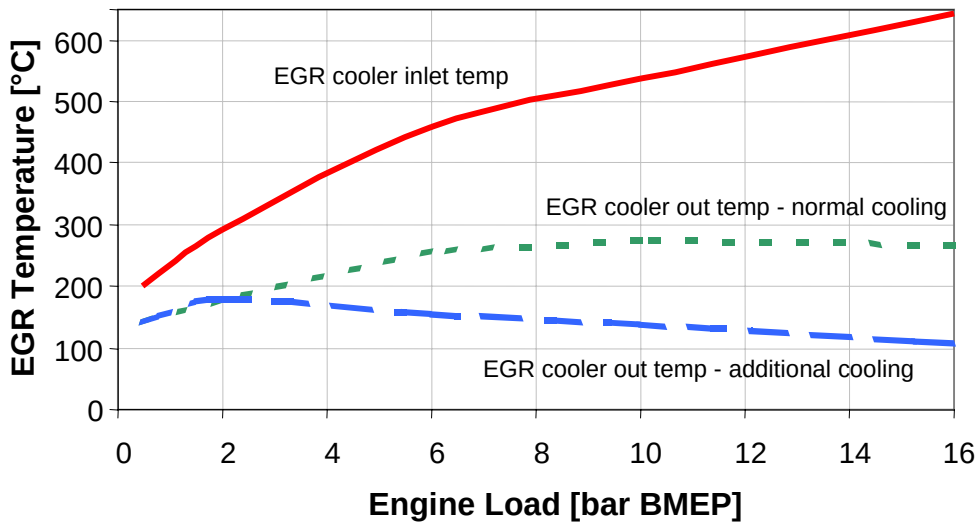
The Ricardo ACTION engine technology roadmap uses an incremental approach to meet the future diesel challenges

LEVEL 1 (T2 Bin 9 LDT, E4+)	LEVEL 2 T2 Bin 8 LDT, Euro 5	LEVEL 3 T2 Bin 5 LDT?, Euro 6?
Air System Developments		
❑ Reduced CR (~17:1) ❑ Variable swirl ❑ EGR bypass	❑ Reduced CR (~16.5:1) ❑ Advanced boosting ❑ Advanced EGR systems & temperature control ❑ Cold start enablers	❑ Reduced CR (~16:1) ❑ Variable Valve Actuation ❑ Advanced cooling strategies
Increased Injection Performance		
Increasing Multiple Injection Capability		
Nozzle Developments		
❑ 7 hole nozzles	❑ +8 hole nozzles ❑ Improved Cd	❑ Variable nozzle technology ❑ Highly Pre-mixed Combustion Concepts
Control		
❑ Lambda sensor	❑ Combustion Feedback Control (CPEMS) ❑ NOx sensor	❑ In-Cycle Model-Based Control (ARTEMIS)
2005	2007/8	+2010

ACTION Level 2 advanced EGR systems enable improved control of combustion temperatures

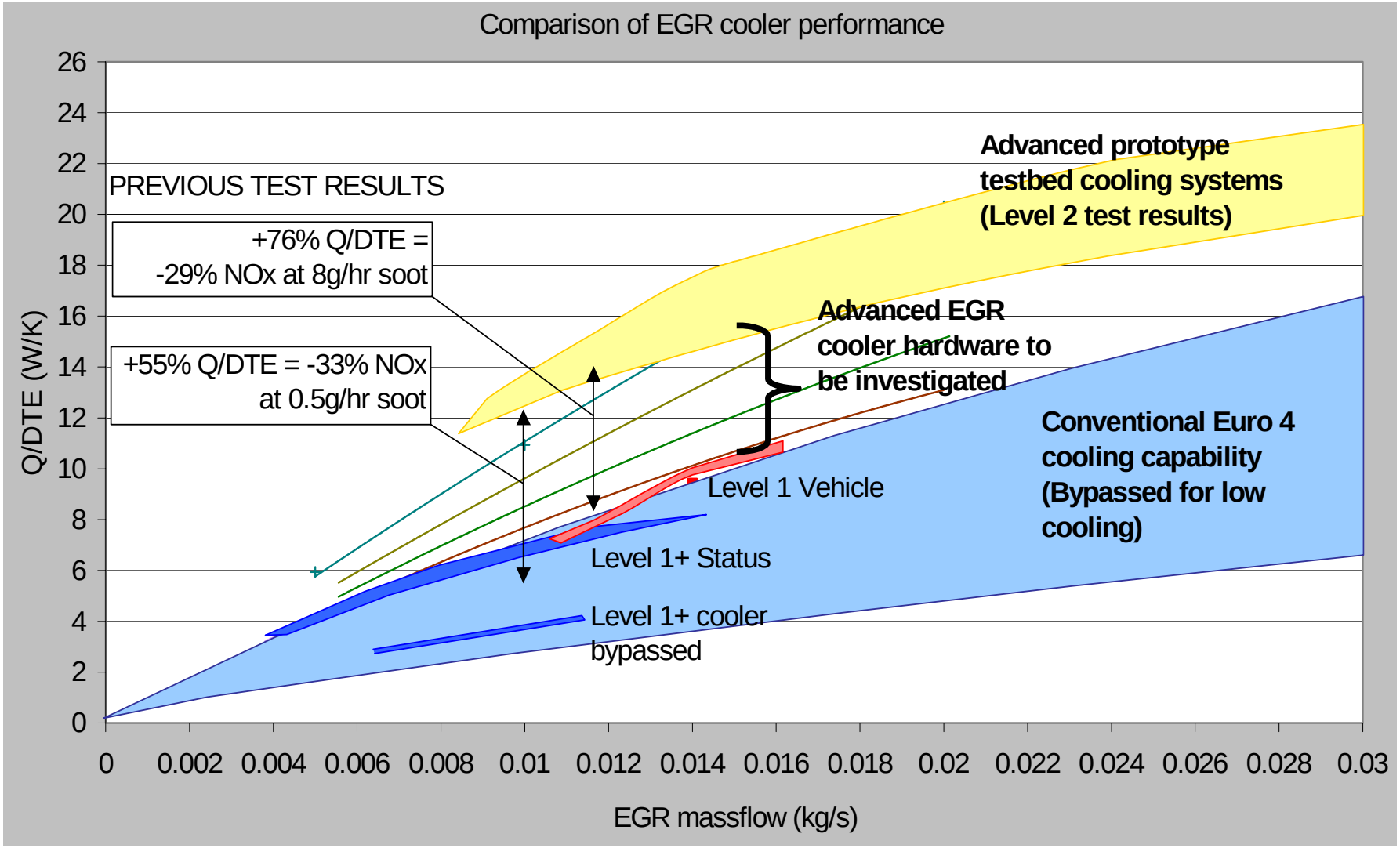


- Cold EGR enables more highly pre-mixed combustion and increased EGR rates
- 25-30% NOx reduction achieved above 6 bar BMEP
- Temperature control is required for light load conditions to avoid HC, CO & FC penalties

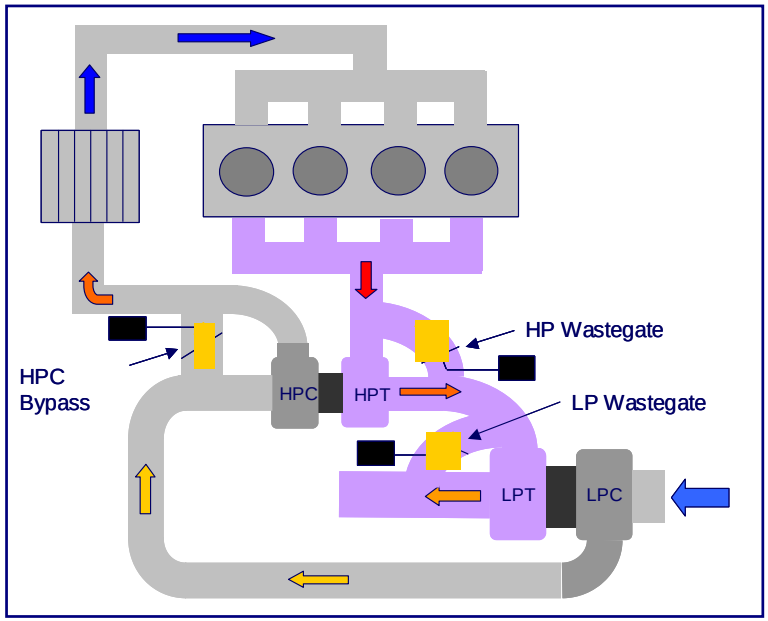


High efficiency EGR cooling hardware will be available to meet Tier 2 & Euro 5 engine system requirements

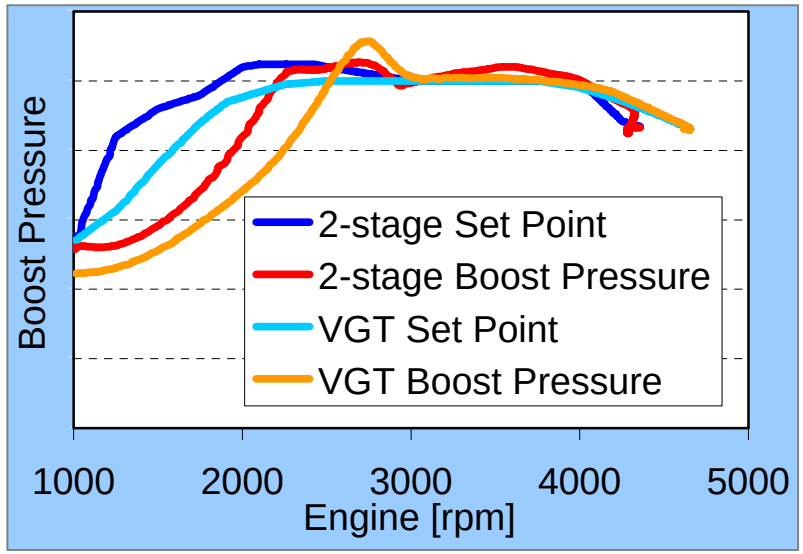
- **Data from Ricardo ACTION advanced air/EGR programs**



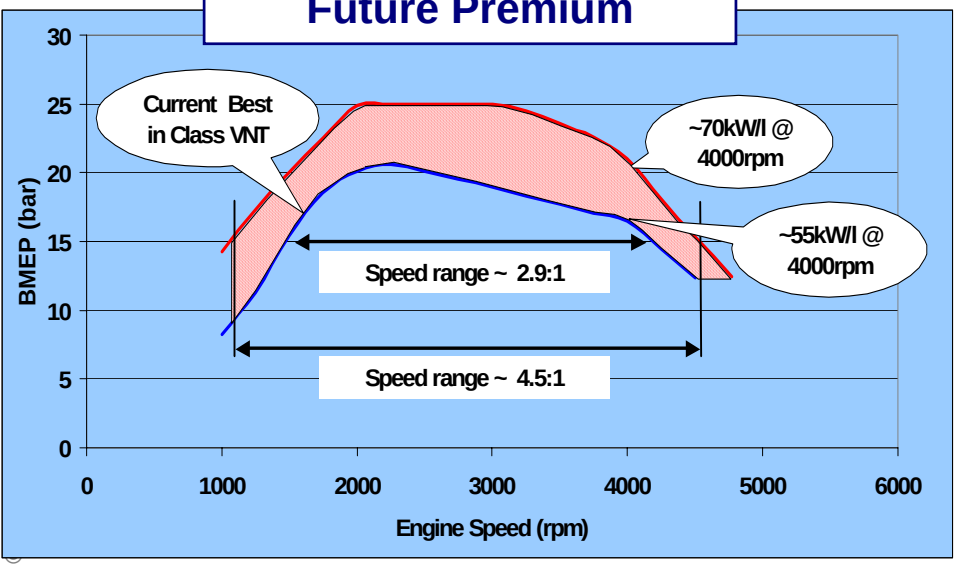
Air system technology will enhance diesel appeal and launch feel while improving emissions and fuel consumption



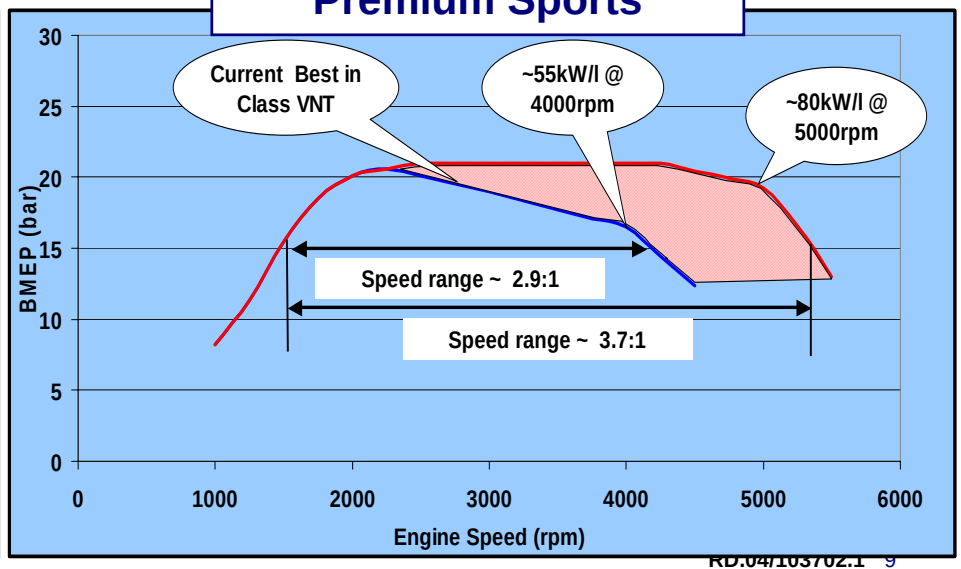
Transient boost control superior to best in class VGT



Future Premium



Premium Sports



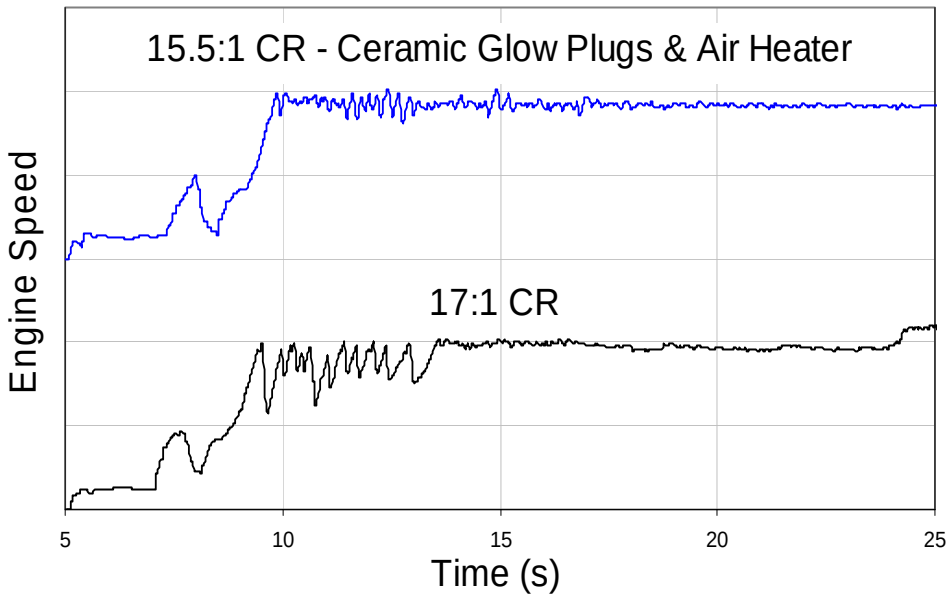
Successful –25°C cold start has been demonstrated at 15.5:1 compression ratio using ceramic glow plug and intake heating

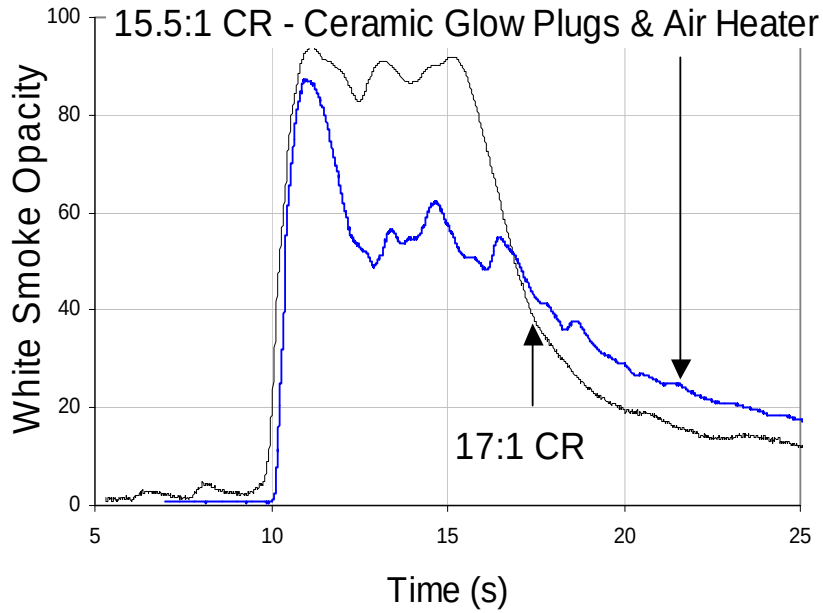
Approach

- NGK air heater activated for 10 sec before glow plug operation
- 40 amp demand only
- NGK NHTC Ceramic glow plug operation of 4 sec before cranking
- Twin pilot injection

Results compared to 17:1 baseline with production glow plugs

- Similar start time (<5 sec) from cranking
- Pre-glow consistent (was 12 sec)
- Stable idle
- Similar or improved smoke opacity





Advanced control technologies are essential to improve diesel engine transient control and production robustness

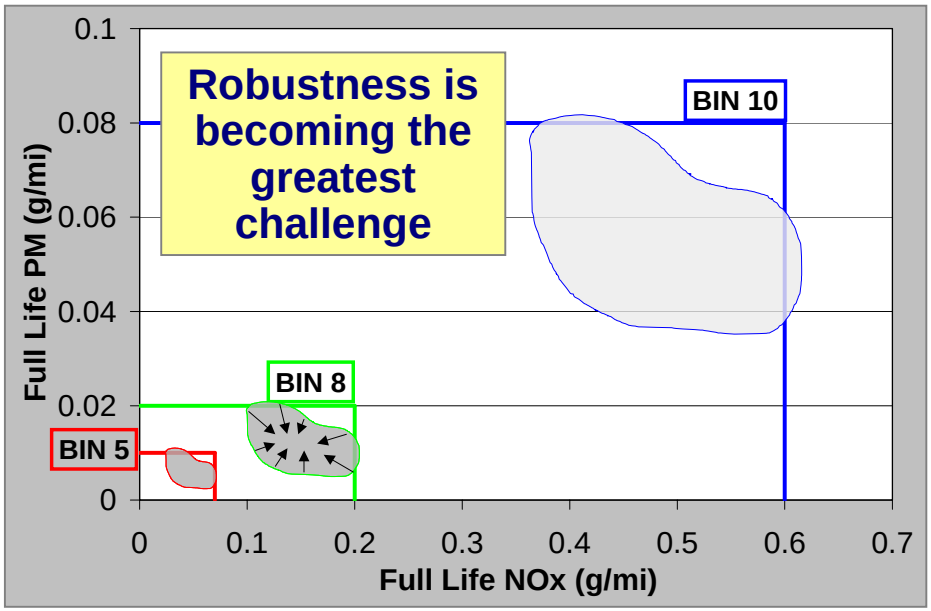
Lambda feedback strategies

Closed loop model based EGR control

Cylinder Pressure Based Engine Management Systems (CPEMS) now being applied to diesel

Automotive Real-Time Engine Modelling by In-cycle Simulation (ARTEMIS)

Ricardo ***RCube*** 500+ MIPS processor developed



Control System Drivers / Benefits

- Emissions & Fuel Economy
- Driveability & Refinement
  - Direct Torque Based Control
- OBD
- Reduced total system cost
- Reduced calibration effort & development time/cost

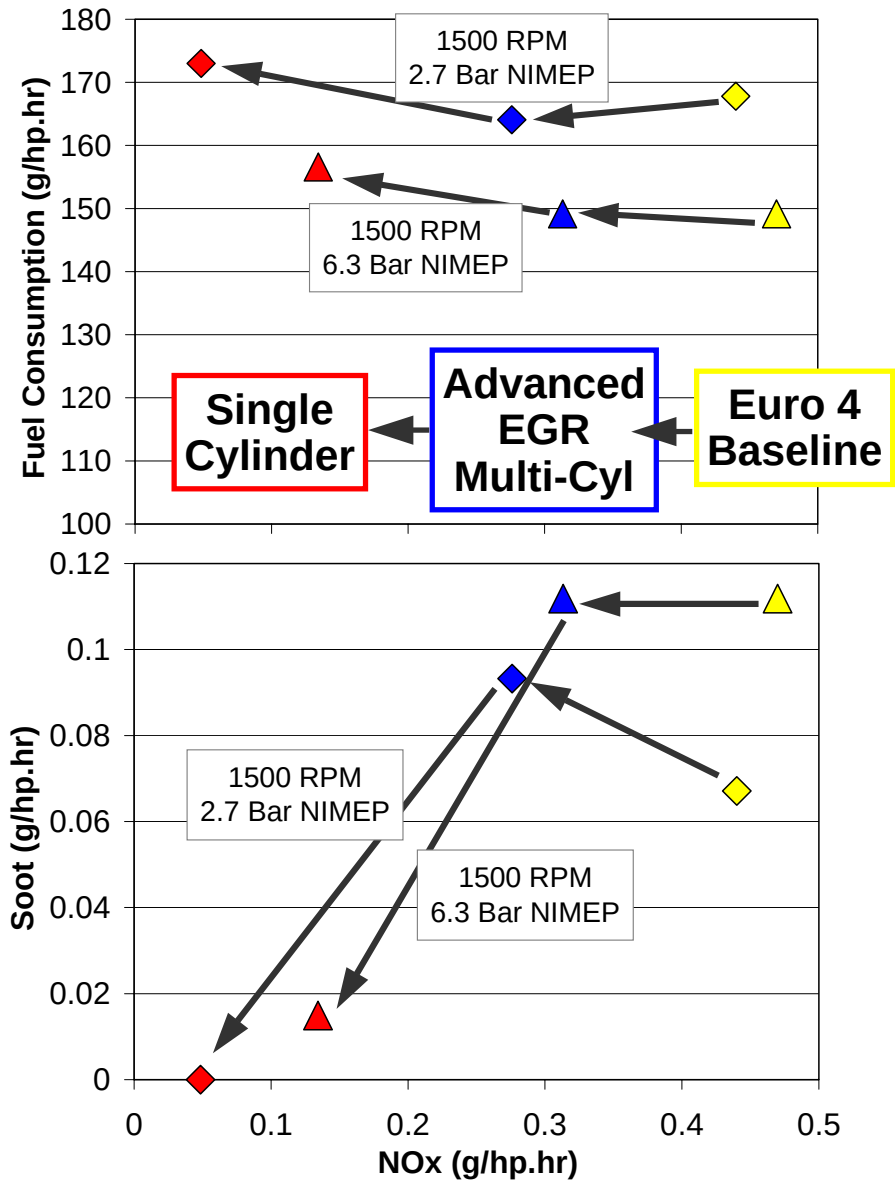
Single cylinder research is developing ACTION Level 3 combustion system & showing potential for further significant NOx reduction

Objectives

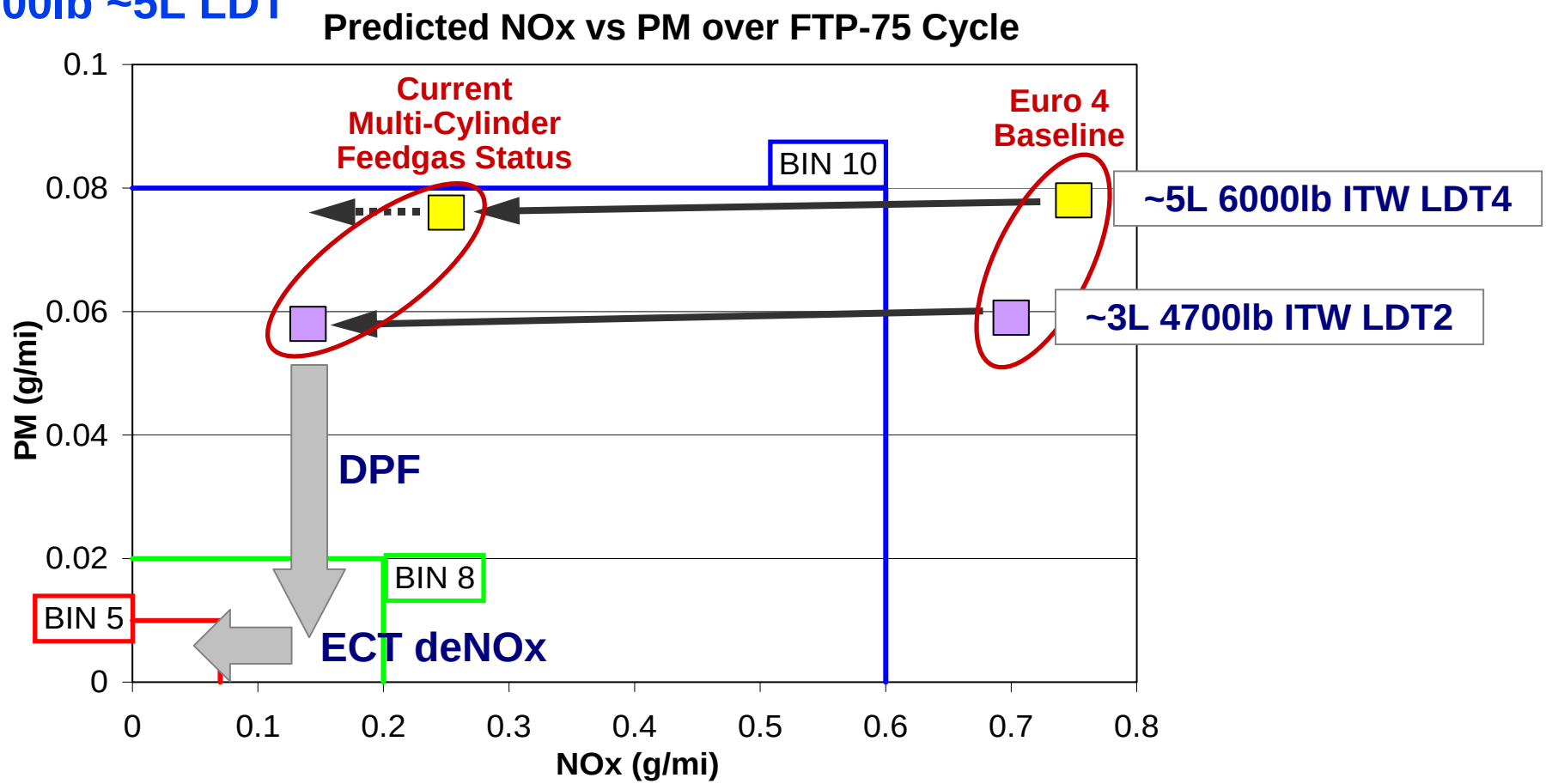
- To deliver a 2010 combustion system design
- To examine the potential for advanced FIE to enable highly pre-mixed and lower temperature combustion
- Enhance CFD combustion system design techniques using optical analysis

Hardware

- Hydra 500 cc Single cylinder
- 16:1 compression ratio combustion system
- New variable swirl port design
- Multiple injection system achieving up to 5 injections
- 7,8, 10 and 12 hole nozzle library



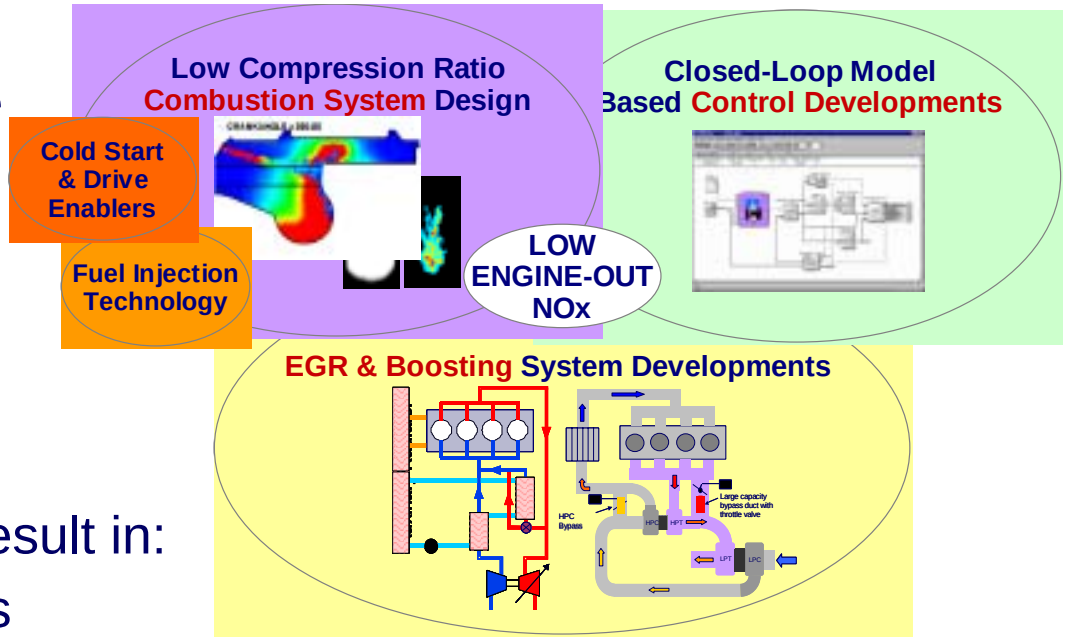
Current multi-cylinder results support first introduction Bin 5 solution with Bin 8 feedgas and ~65% aftertreatment deNOx for 6000lb ~5L LDT



Application	Cycle	Target NOx without deNOx ECT (g/mi)	Estimated ECT deNOx Requirement (%)
5L 6000lb ITW LDT4	Bin 5 Full Life	0.18	65%
	US06 4k	0.54	0%
3L 4700lb ITW LDT2	Bin 5 Full Life	0.14	50%
	US06 4k	0.34	35%

Summary: ACTION technologies offer an integrated approach to deliver competitive US diesels within a viable business case

- The operating range of highly pre-mixed combustion can be enhanced
  - Practical solutions are under development
  - Robustness is becoming the most critical challenge



- An integrated approach will result in:
  - Aftertreatment cost savings
  - Improved engine performance
  - Optimized the trade-off between fuel consumption, NOx and cost
  - Improved refinement (transient control and combustion noise)

- Engine out NOx reduction combined with minimum NOx aftertreatment offers the best potential to achieve Bin 5 and US06 emissions for ’07/’08 first Tier 2 introductions