RICARDO

Challenges of Meeting Tier2 Bin2 Tailpipe Emissions

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Technology Developments are Required to Support the Anticipated Growth in Light Duty Diesel Vehicles

- US regulations will increase the emphasis on improved fuel economy: 40% improvement in CAFE may be required by 2020
- $3/gal gasoline and environmental concerns are changing the US vehicle market

- US consumers are gaining appreciation of modern diesel vehicle characteristics
- Most manufacturers have committed to launch diesels in the US. Trend of large V8 engines will move to smaller engine and vehicle segment

- Diesel is a lower cost option compared to gasoline hybrids; even accounting for the “clean” technology needed to meet US emissions legislation
- Ricardo forecasts growth in both technologies but expects diesel to prevail by 2012 (1.5mn units vs. 1.2mn hybrids)

- The cost penalty of emissions control is the greatest challenge to success
- LNT or SCR aftertreatment is currently required for Tier 2 Bin 5. However low NOx technology developments will reduce powertrain costs

Advanced Diesel Technologies Offer Fuel Economy Benefits Under All Conditions Without Compromising Performance

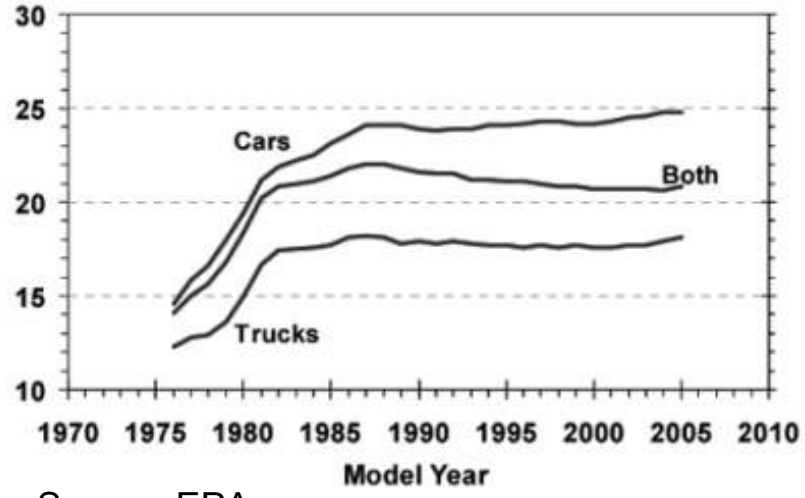
+ Opportunities

- Robust fuel economy and low CO_2 benefits under all operating conditions
- Improved performance & towing
  - High torque from low engine speeds gives 'fun-to-drive' characteristic
- Lower total system cost than full hybrid gasoline
- Bio-diesel offers improved well-to-wheels CO_2 benefit compared to Ethanol

– Risks/Challenges

- Cost of emissions solutions
- Poor consumer image of legacy products
- Gasoline/diesel refinery split will become a challenge if diesel market grows significantly
- Cetane variability and environmental challenges
- Limited re-fueling infrastructure
- Urea infrastructure required for products adopting SCR
- Threat of new gasoline engine technology

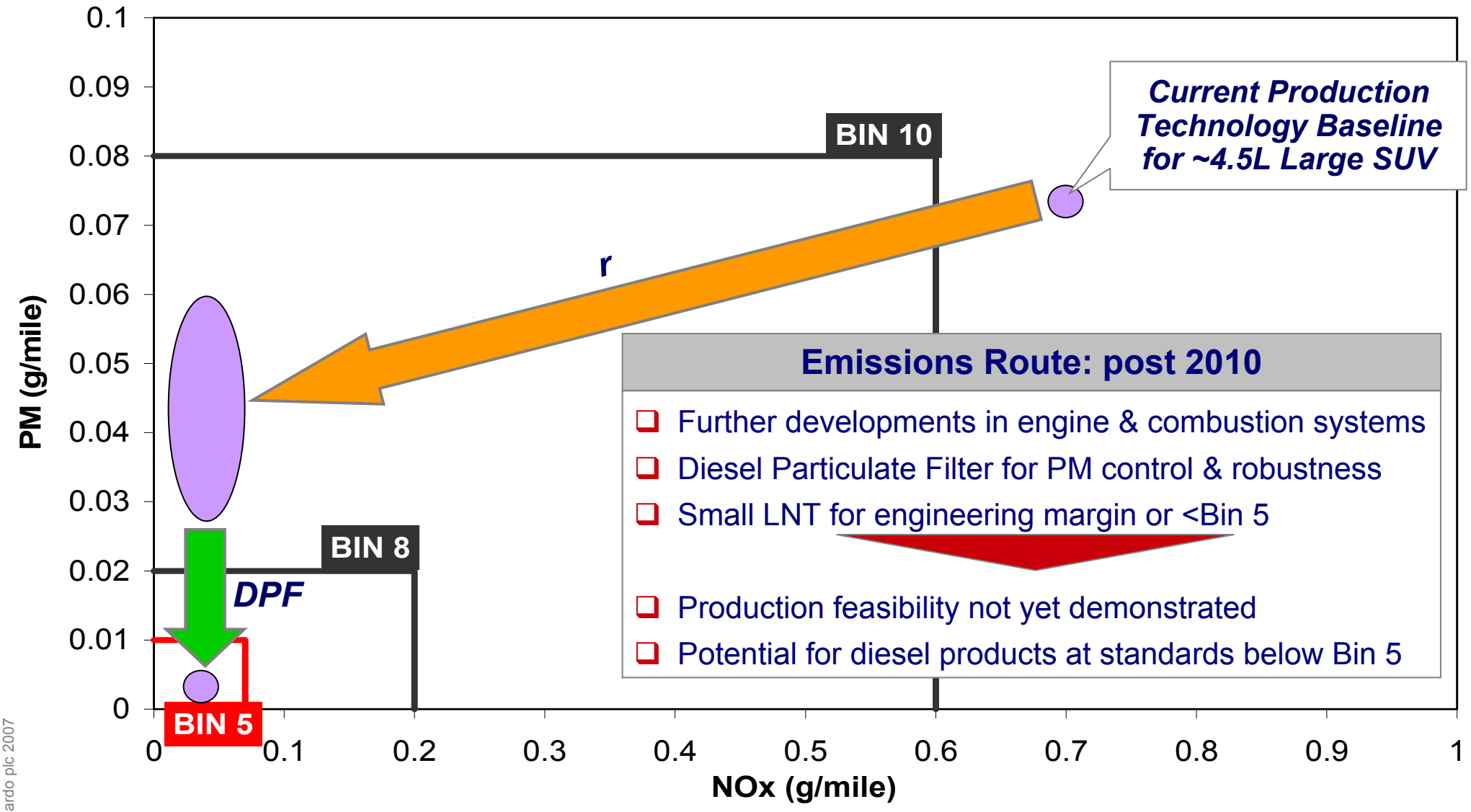
Adjusted Fuel Economy by Model Year
(3 Year moving average)



Source: EPA

What role will diesel engines play in meeting tougher CAFE and CO_2 demands?

Engine research is targeting Bin 5 engine out NOx



Large Ricardo Research Program is Addressing T2B2 Challenges

LDD Bin5 EO - Bin 2 TP | **Vehicle Demo Achieving US Tier 2 Bin 2 Limits**

Project Timing: September 2005 to December 2007

Objectives

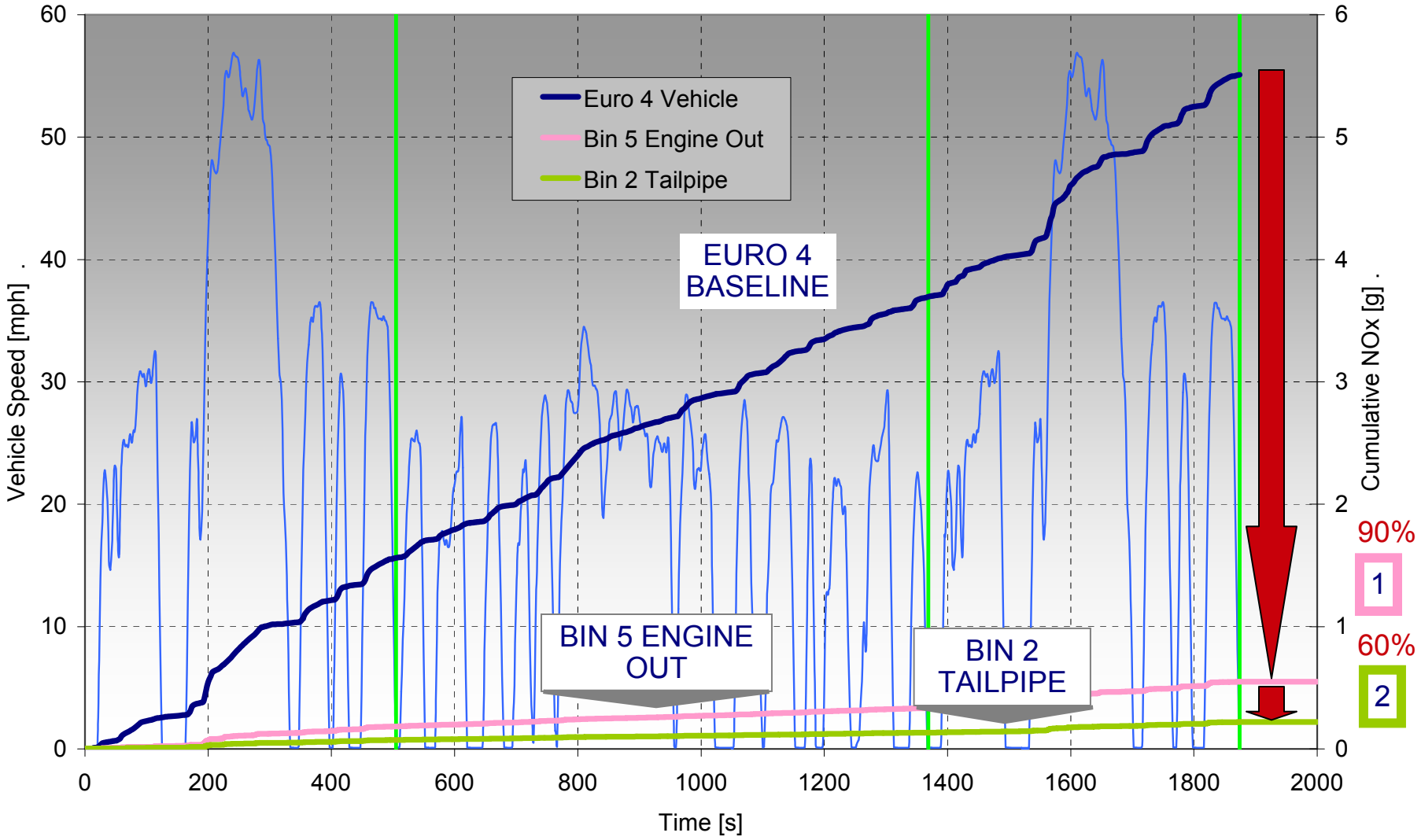
- To achieve US Tier 2 Bin 2 tailpipe and Bin 5 engine out emission on D class passenger car
- To develop a novel air handling technology (Boost + EGR)
- To develop an integrated aftertreatment system (LNT + DPF)
- To exploit the capabilities of Ricardo in-cylinder combustion control (CPEMS)

Status and Results

- Novel 2 stage series sequential boost system defined
- Full engine map demonstrating Bin 5 engine out NOx target completed
- Air system and aftertreatment vehicle packaging completed
- First vehicle built and ready for commissioning
- Bin 5 engine out on vehicle September 2007
- Bin 2 tailpipe on vehicle December 2007

Strategy Uses Combination of Engine Out and Tailpipe NOx Reductions

- Step 1 – 90% NOx reduction by engine technology
- Step 2 – 60% NOx reduction by LNT



The Ricardo ACTION engine technology roadmap
"Advanced Combustion Technology for Improved engine Out NOx"

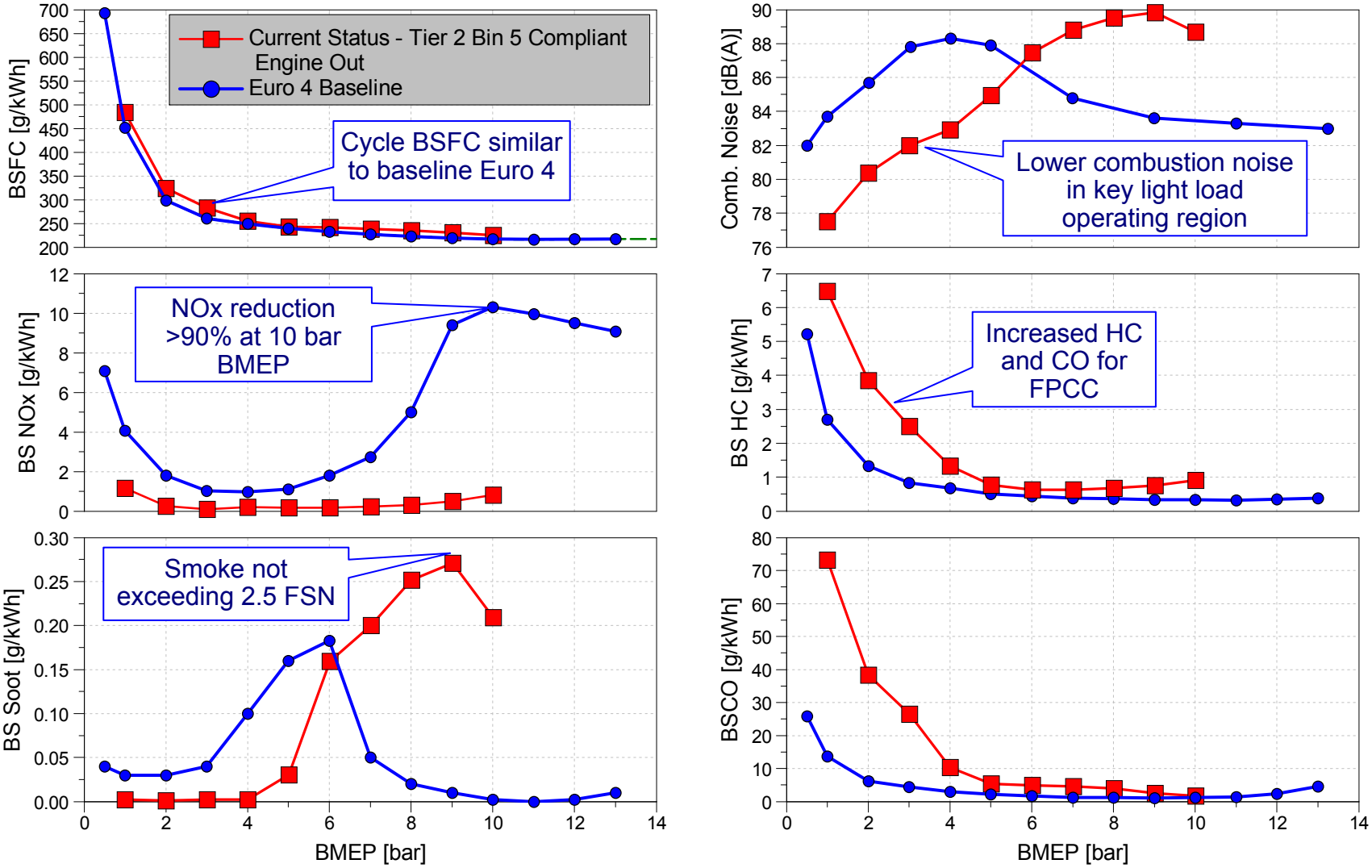
LEVEL 1 (T2 Bin 9 LDT, Euro 5 without NOx A/T)	LEVEL 2/2+ (T2 Bin 8 LDT, E6 without NOx A/T)	LEVEL 3 (T2 Bin 5 LDV, E6 SUV? without NOx A/T)	LEVEL 4 (TBC) (T2 Bin 5 LDT? without NOx A/T)
Air System Developments			
❑ Variable swirl ❑ EGR bypass ❑ 1 Stage VGT	❑ Enhanced EGR cooling & temperature control ❑ Level2+ = Low Pressure EGR	❑ Advanced boosting & cooling strategies ❑ Low Pressure EGR	❑ Variable Valve Actuation
Combustion System Developments			
❑ Reduced CR (~17:1) ❑ 7 hole nozzles	❑ Reduced CR (16-16.5) ❑ +8 hole nozzles	❑ Reduced CR (15.5-16:1) ❑ Highly Pre-mixed Combustion	❑ Variable nozzle technology
Injection strategies enhanced for low NOx combustion			
Enhanced fuel injection performance			
Control System Developments			
❑ Lambda sensor	❑ NOx sensor (app. specific)	❑ Combustion Feedback Control (CPEMS)	❑ In-Cycle Model-Based Control (WAVE®-RT)
2005	2007/8	2010	2012+

Key Ricardo Advanced Technologies Applied to Achieve Targets

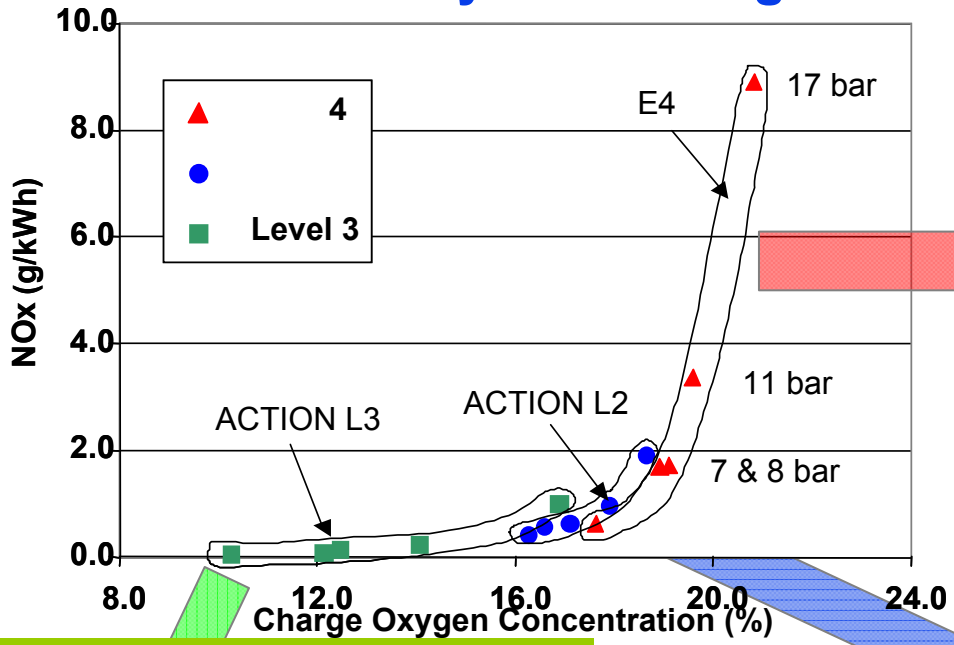
- Two-stage series-sequential turbocharging and low pressure EGR layout
- Two-stage EGR cooling with separate low temperature circuit
- Advanced DOC
- LNT in-cylinder rich spike calibration
- LNT+DPF close coupled
- New boost/EGR control and warm up strategies
- Closed-loop cylinder pressure control (CPEMS)

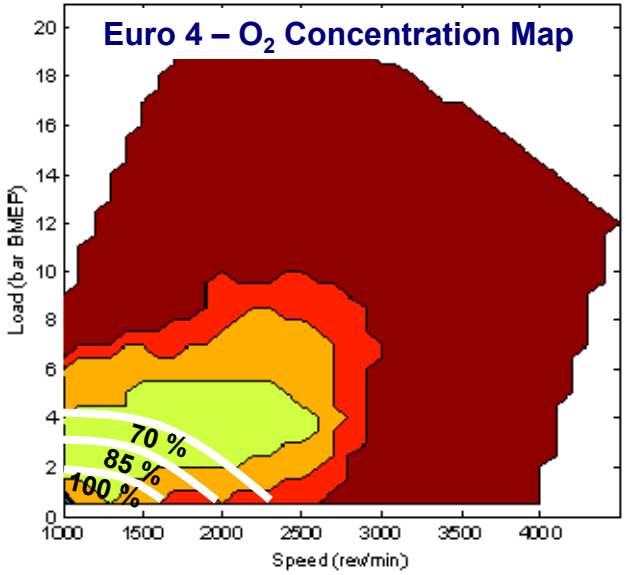
Testbed Results Demonstrate the Potential to Achieve T2B5 in a 3500 lbs Auto Transmission Vehicle Without NOx Aftertreatment

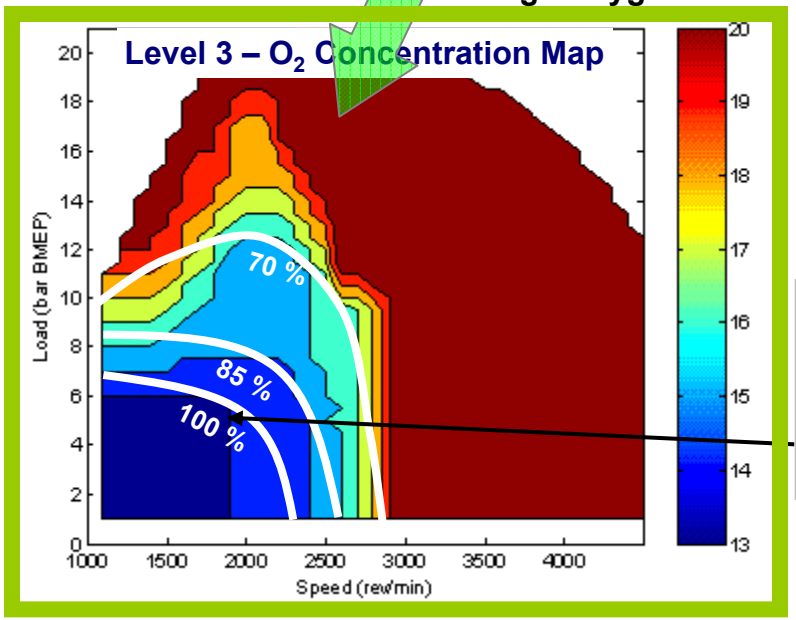
Comparison of Bin 5/US06 and Baseline Euro 4 Engine Results
1500 rev/min 1-10 bar BMEP Load Range

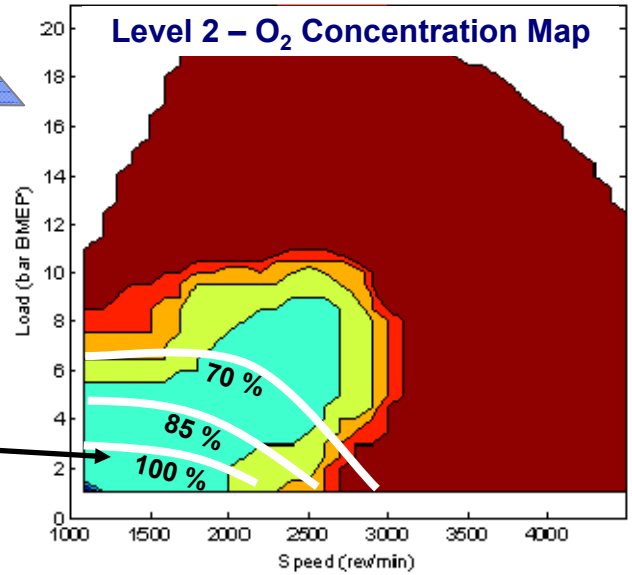


Oxygen concentration reduction by lowering air/fuel ratio and raising EGR rates is the key to lowering NOx emissions





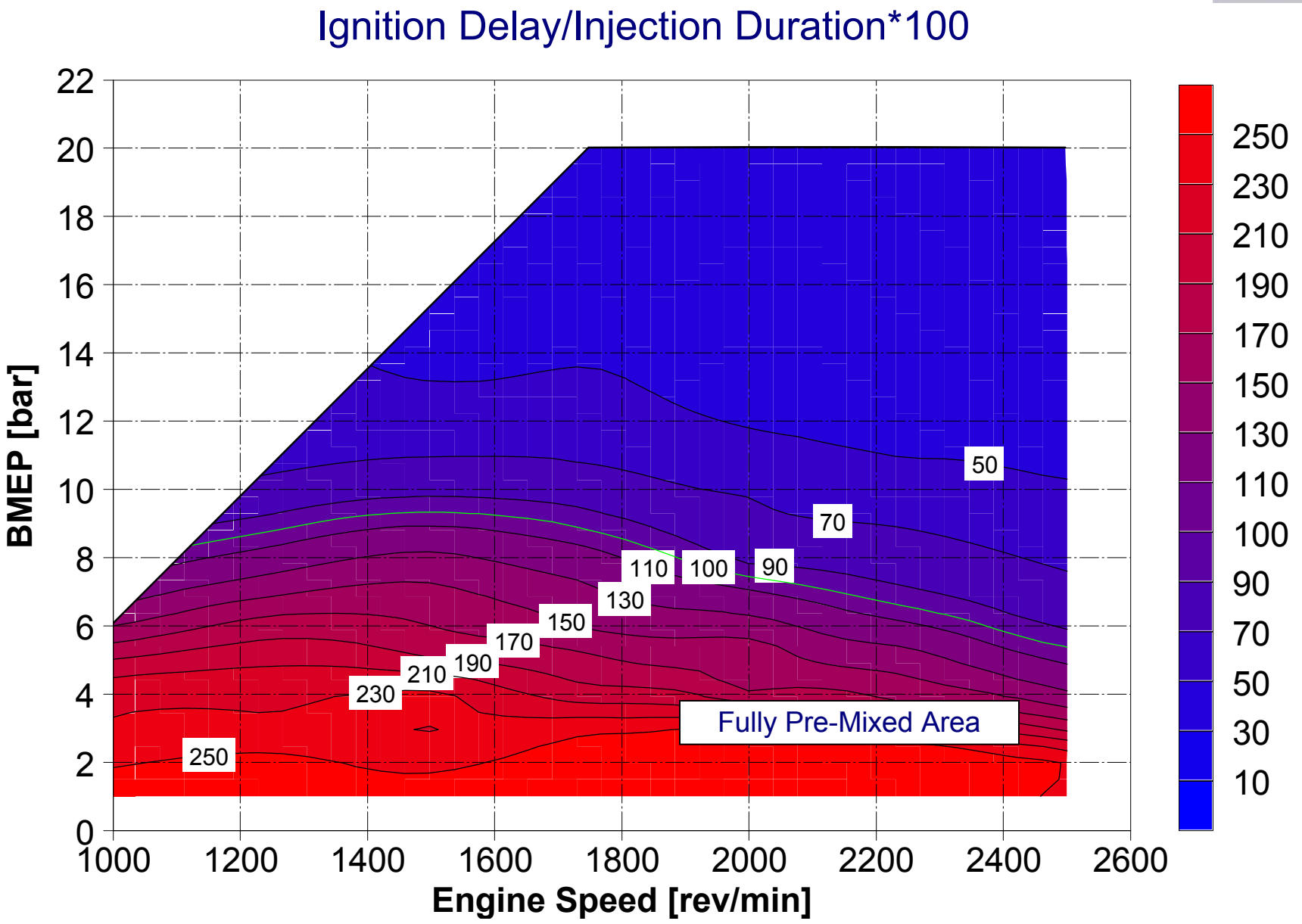




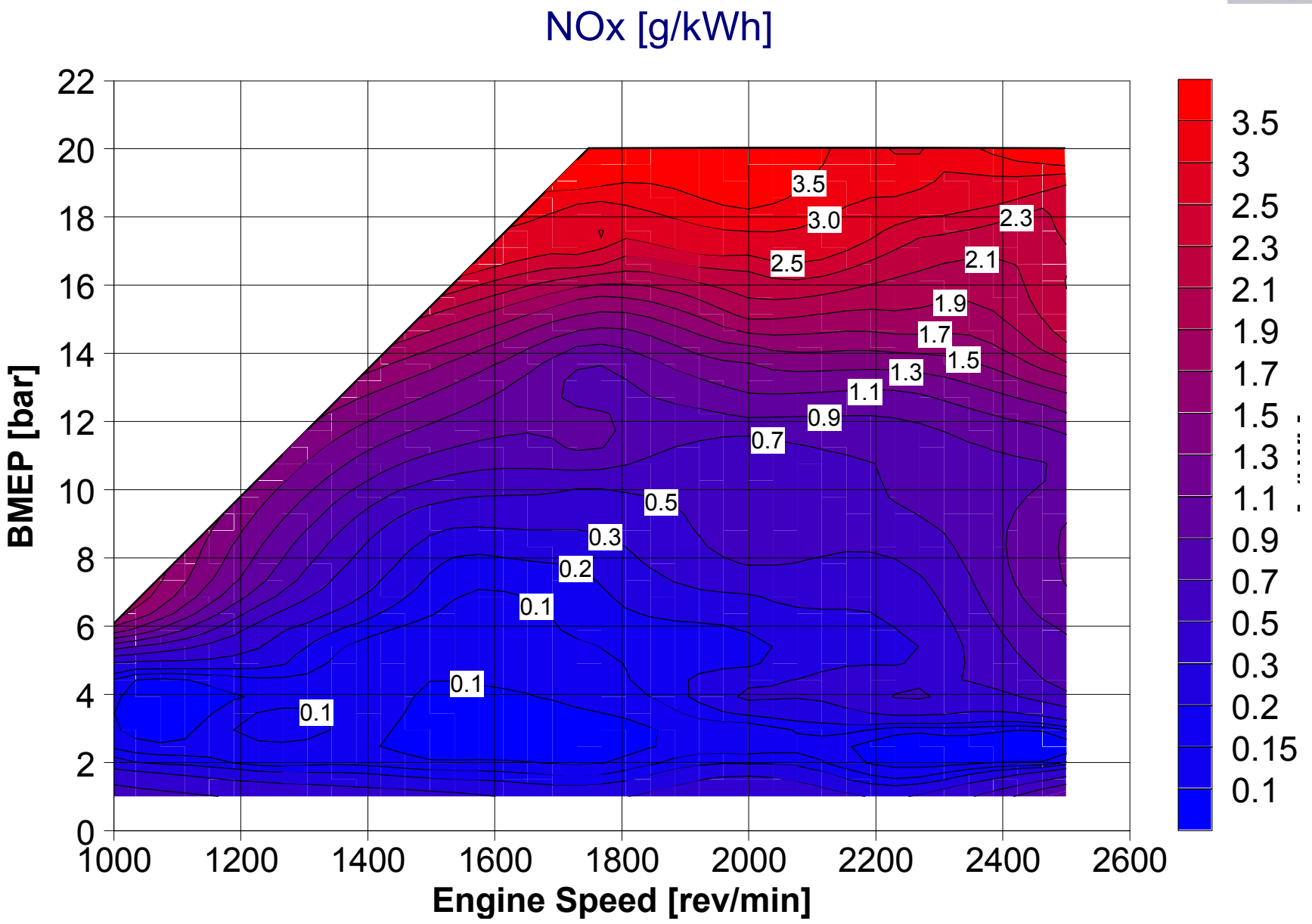
Numbers indicate percentage of fuel injected before start of combustion of the main injection

Reference:
Ricardo SAE06-01-1145

Fully Pre-Mixed Combustion Utilized Over a Wide Operating Range



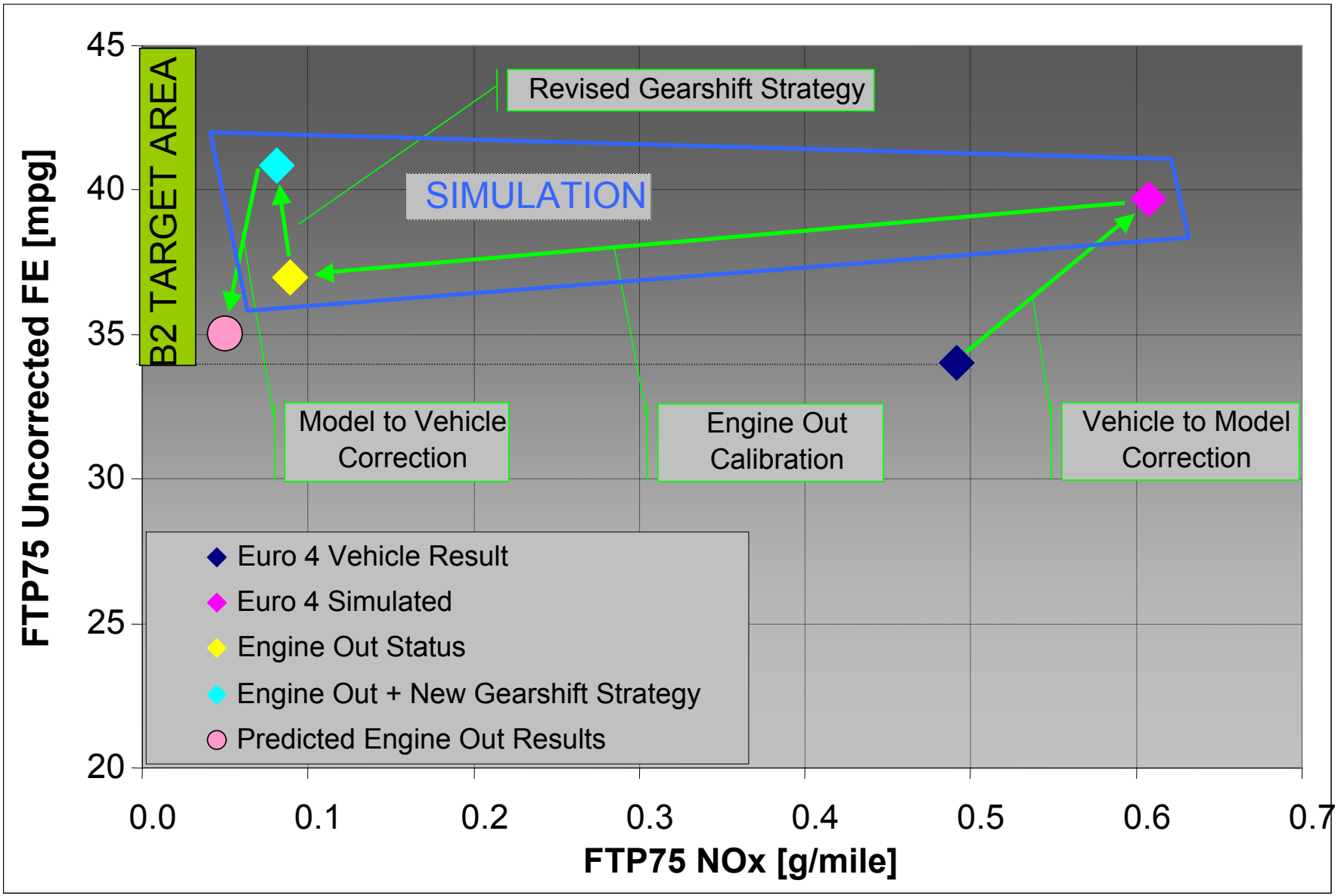
Specific NOx Emission Target Achieved on Testbed



Applying an LNT to a Bin 5 Engine Achieves Bin 2 Tailpipe Emissions with Minimum LNT Volume

- Objective: minimize fuel consumption and tailpipe emissions and have a LNT regeneration event which is not noticeable to the driver
- T2B2 layout is not using an exhaust injector, therefore the rich event must be managed using air and fuel system interventions only
  - Strategy limits large post injections to:
    - Minimize Oil dilution
    - Utilize CO as the preferred reductant (better than HC)
    - Minimize torque variation / Less noticeable to the driver
- Accomplish this while maintaining neutral combustion noise and driveability
- Results:
  - Developed a rich spike strategy that accomplishes these requirements
  - Reduced LNT volume by ~50% by achieving Bin 5 Engine-out NOx levels

Simulations Based on Latest Testbed Results Confirm Bin 5 Engine Out Feasibility



Conclusions

- Many challenges exist in meeting future Tier 2 Bin 2 legislation with cost effective solutions
- Ricardo research is showing potential for:
  - Tier 2 Bin 5 emissions without NOx aftertreatment
  - Tier 2 Bin 2 with simplified LNT NOx aftertreatment
  - While maintaining a 30% fuel economy benefit over the gasoline variant
- Current development is directed at:
  - Simplification: potential/cost down analysis
  - Further fuel economy improvements
- Vehicle demonstrator roll out in 2008