Challenges of Meeting Tier2 Bin2 Tailpipe Emissions

DEER 2007 Conference
Detroit, 13 August 2007

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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 CO₂ 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 CO₂ 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

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**Adjusted Fuel Economy by Model Year**

(3 Year moving average)

Source: EPA

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**What role will diesel engines play in meeting tougher CAFE and CO₂ demands?**
Engine research is targeting Bin 5 engine out NOx

Current Production Technology Baseline for ~4.5L Large SUV

Emissions Route: post 2010

- Further developments in engine & combustion systems
- Diesel Particulate Filter for PM control & robustness
- Small LNT for engineering margin or <Bin 5
- Production feasibility not yet demonstrated
- Potential for diesel products at standards below Bin 5
# 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

<table>
<thead>
<tr>
<th>Objectives</th>
<th>Status and Results</th>
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<tr>
<td>- To achieve US Tier 2 Bin 2 tailpipe and Bin 5 engine out emission on D class passenger car</td>
<td>- Novel 2 stage series sequential boost system defined</td>
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<tr>
<td>- To develop a novel air handling technology (Boost + EGR)</td>
<td>- Full engine map demonstrating Bin 5 engine out NOx target completed</td>
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<td>- To develop an integrated aftertreatment system (LNT + DPF)</td>
<td>- Air system and aftertreatment vehicle packaging completed</td>
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<td>- To exploit the capabilities of Ricardo in-cylinder combustion control (CPEMS)</td>
<td>- First vehicle built and ready for commissioning</td>
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<tr>
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<td>- Bin 5 engine out on vehicle September 2007</td>
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<tr>
<td></td>
<td>- Bin 2 tailpipe on vehicle December 2007</td>
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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

![Graph showing vehicle speed against cumulative NOx emissions, with two steps of reductions indicated: 90% from engine out and 60% from tailpipe.](image)
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)

- Variable swirl
- EGR bypass
- 1 Stage VGT

LEVEL 2/2+
(T2 Bin 8 LDT, E6 without NOx A/T)

- Enhanced EGR cooling & temperature control
- Level2+ = Low Pressure EGR

LEVEL 3
(T2 Bin 5 LDV, E6 SUV? without NOx A/T)

- Advanced boosting & cooling strategies
- Low Pressure EGR

LEVEL 4 (TBC)
(T2 Bin 5 LDT? without NOx A/T)

- Variable Valve Actuation

Air System Developments

- Reduced CR (~17:1)
- 7 hole nozzles

Combustion System Developments

- Reduced CR (16-16.5)
- +8 hole nozzles

- Reduced CR (15.5-16:1)
- Highly Pre-mixed Combustion

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)

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

- Current Status - Tier 2 Bin 5 Compliant Engine Out
- Euro 4 Baseline

Cycle BSFC similar to baseline Euro 4

NOx reduction >90% at 10 bar BMEP

Smoke not exceeding 2.5 FSN

Lower combustion noise in key light load operating region

Increased HC and CO for FPCC

Engine Out

NOx reduction
Oxygen concentration reduction by lowering air/fuel ratio and raising EGR rates is the key to lowering NOx emissions.
Fully Pre-Mixed Combustion Utilized Over a Wide Operating Range

Ignition Delay/Injection Duration*100

Engine Speed [rev/min]

BMEP [bar]

Fully Pre-Mixed Area
Specific NOx Emission Target Achieved on Testbed

NOx [g/kWh]

BMEP [bar]

Engine Speed [rev/min]

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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

- Euro 4 Vehicle Result
- Euro 4 Simulated
- Engine Out Status
- Engine Out + New Gearshift Strategy
- Predicted Engine Out Results

Graph showing FTP75 NOx [g/mile] vs. FTP75 Uncorrected FE [mpg] with various markers and lines indicating different simulation and correction scenarios.

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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