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

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

**Opportunities**

- CAFE improvement & CO₂ 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.

Gasoline vs Diesel Fuel MPG - European Light Duty Vehicles

<table>
<thead>
<tr>
<th>Gross Vehicle Weight (lb)</th>
<th>Combined Cycle MPG (US)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>0</td>
</tr>
<tr>
<td>6000</td>
<td>60</td>
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Diesel average +45% MPG benefit
Engine technologies to reduce NOx at source and minimize NOx aftertreatment offers the most viable business case.

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

APPROACH

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

Source: MTZ 11/2002: Toyota

Temperature /K

Local Equivalence Ratio

Soot formation area

NOx formation area
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)

- **Closed-Loop Model Based Control Developments**
  - CONTROL DEVELOPMENTS ENABLE IMPROVED REFINEMENT & REDUCED COMPONENT COSTS

- **Fuel Injection Technology**
  - 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+)
- Reduced CR (~17:1)
- Variable swirl
- EGR bypass

**LEVEL 2**
(T2 Bin 8 LDT, Euro 5)
- Reduced CR (~16.5:1)
- Advanced boosting
- Advanced EGR systems & temperature control
- Cold start enablers

**LEVEL 3**
(T2 Bin 5 LDT?, Euro 6?)
- Reduced CR (~16:1)
- Variable Valve Actuation
- Advanced cooling strategies

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**Air System Developments**
- 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)

- Increasing Injection Performance

<table>
<thead>
<tr>
<th>Year</th>
<th>LEVEL 1</th>
<th>LEVEL 2</th>
<th>LEVEL 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2007/8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+2010</td>
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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

PREVIOUS TEST RESULTS

+76% Q/DTE = -29% NOx at 8g/hr soot

+55% Q/DTE = -33% NOx at 0.5g/hr soot

Advanced prototype testbed cooling systems (Level 2 test results)

Advanced EGR cooler hardware to be investigated

Conventional Euro 4 cooling capability (Bypassed for low cooling)

Level 1 Vehicle

Level 1+ Status

Level 1+ cooler bypassed

Comparison of EGR cooler performance
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

Current Best in Class VNT

~70kW/l @ 4000rpm

Speed range ~ 2.9:1

~55kW/l @ 4000rpm

Speed range ~ 4.5:1

Engine Speed (rpm)

BMEP (bar)

BMEP (bar)

Speed range ~ 2.9:1

Engine Speed (rpm)

BMEP (bar)

Speed range ~ 3.7:1

Engine Speed (rpm)
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

![Graph showing engine speed and white smoke opacity over time for 15.5:1 CR and 17:1 CR with ceramic glow plugs and air heater compared to baseline.](chart)
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

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

Predicted NOx vs PM over FTP-75 Cycle

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