Meeting the Euro-3 Challenge for 4-Stroke Motorcycles: Background

- China is following the European pattern for regulating emissions from on-road motorcycles
- Euro-2 level emissions regulations have been in force for new motorcycles in Europe since 2003, China is now beginning implementation of Euro-2 regulations
- Euro-3 will come into force in Europe in 2006, China in the future (?)
- Euro-2 is relatively easy to meet for 4-stroke motorcycles
  - Improvements in engine design, tuning and performance such as EFI
  - Secondary air injection (SAI) to target CO emissions
  - Simple oxidation catalysts in either heat tube or monolith form sometimes with SAI
- However, meeting Euro-3 is a difficult, but attainable, technological leap
Meeting Euro-3 Emission Regulations Will Become More Difficult Due to Significant Changes From Current Euro-2 Standards

- HC will be 33% to 70% lower than Euro-2
- CO will be 65% lower than Euro-2
- NOx will be 50% lower than Euro-2
- Cold start requirement will be added (increases HC & CO)
- High speed EUDC added for engines >150cc (increases NOx and CO)
- 30K km durability added for engines >270cc
- 18K km durability added for engines 170 to 269cc
- 12K km durability added for engines 51cc to 168cc

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Homologation/Production (COP) Mass Emissions (g/km)</th>
<th>Durability</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HC  CO  NOx Test Cycle</td>
<td>Test</td>
<td></td>
</tr>
<tr>
<td>All 4-stroke</td>
<td>3   13  0.3 ECE R40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.4-5 &lt;150cc</td>
<td>1.2  5.5  0.3 ECE R40</td>
<td></td>
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</tr>
<tr>
<td>2.4-5 &gt;150cc</td>
<td>1    5.5  0.3 ECE R40</td>
<td></td>
<td>Stage 2 for new models as of 1/1/2003</td>
</tr>
<tr>
<td>2.4-6 &lt;150cc</td>
<td>0.8  2   0.15 Cold Start ECE R40 12K km</td>
<td></td>
<td>Stage 2 Tax Incentive/Proposed 2006 Stage 3</td>
</tr>
<tr>
<td>2.4-6 &gt;150cc</td>
<td>0.3  2   0.15 Cold Start ECE R40+EUDC 18K &amp; 30K km</td>
<td></td>
<td>Stage 2 Tax Incentive/Proposed 2006 Stage 3</td>
</tr>
</tbody>
</table>

Cumulative Emissions Trace for a Typical Current 4-S EFI Motorcycle with Catalyst for the current ECE R40 Test (Euro-2)

- Euro-2 Warm-up Phase
- Euro-2 ECE R40 Cycle
- EUDC not required
- CO, HC, NOx, Vehicle Speed, km/h
Cumulative Emissions Trace for a Typical Current 4-S EFI Motorcycle with Catalyst for Cold Start ECE R40 + EUDC (Euro-3)

Elimination of Warm-up Phase and Addition of EUDC Causes Significant Changes to Final Emissions

- **HC and CO**
  - Most HC and CO are produced in the warm-up phase
  - Elimination of warm-up will result in significantly higher HC and CO
  - Catalyst light-off is a factor and must be improved to minimize HC and CO

- **NOx**
  - Most NOx is produced in EUDC portion of test
  - Addition of EUDC will result in much higher NOx unless NOx performance of catalyst is improved
Ways to Improve Catalyst Light-off for Better HC and CO Performance

- Higher PM loading (increases active PM sites)
- Higher dispersion of PM to create more actives sites and reduce the effects of sintering and poisoning (also improves durability)
- Higher cell density substrates (increase surface area = better PM dispersion)
- Optimum positioning of catalyst higher temperature location (but not too hot to cause damage to catalyst)
- Use of close-mounted “light-off” catalysts using specially designed washcoat components that are high temperature resistant (can survive closer to engine)
- Lighter weight substrate (thinner foils have less thermal mass to overcome)

Ways to Improve NOx Performance

- Higher PM (Rh) loading
- Better utilization of Rh
  - Segregated washcoat (minimize potential alloying problems with other PMs)
  - Layering of washcoat
- NOx is space velocity (catalyst volume/ exhaust flow rate) sensitive
  - Larger substrate
  - Higher cell density
- Use of closed-loop engine control with three-way catalyst technology (TWC)
Three-Way Catalysts (TWC) Are Only Effective Close to Stoichiometry

- Too “Rich”: Insufficient O₂ to convert CO & HCs
- Too “Lean”: Excess O₂ makes it hard for the NOₓ molecules to compete for catalytic sites
- Stoichiometry: Just enough oxidants (O₂ & NOₓ) to react with the reductants (CO & HCs) for optimum HC, CO, & NOₓ conversions

“Perturbated” Flow is an Important Factor in TWC Design

- To maintain stoichiometric engine-out gas composition, we use an oxygen sensor in a feedback loop which controls engine fueling
- Just like a thermostat, the composition fluctuates around the desired value
- This “perturbation” causes a problem
  - Half the time, there’s more oxygen than can be used
  - Half the time there’s not enough oxygen
Ceria Solves this Problem by Switching Valences and “Storing Oxygen”

• During the lean half-cycle, ceria adsorbs excess $O_2$ that would otherwise escape

$$\text{Ce}^{\text{III}}_2\text{O}_3 + \frac{1}{2} \text{O}_2 \rightarrow 2 \text{Ce}^{\text{IV}}\text{O}_2$$

• During the rich half-cycle, CO reacts with this adsorbed $O_2$ forming $\text{CO}_2$

$$2 \text{Ce}^{\text{IV}}\text{O}_2 + \text{CO} \rightarrow \text{Ce}^{\text{III}}_2\text{O}_3 + \text{CO}_2$$

Proprietary Segregated Washcoat Process Allows Atomic Scale Engineering of Catalyst to Enhance PM Performance

• Precious Metals (Pt, Pd, Rh) Can be Atomically Dispersed on Specific Base Metal Supports (Alumina, Ceria)

  \begin{align*}
  \text{Rh/BMO-1} & \\
  \text{Pt/BMO-2} & 
  \end{align*}

• Allows Specific Promotion of Precious Metal Function

• Avoids Formation of Poorer Performing Alloys and PM/BMO Compounds
Segregated Materials Can Be Layered Giving Engineered Architecture

Enhances NOx Conversion by Localizing Rh in Region Exposed to High Reductant (CO) Concentration

Meeting Euro-3 Will Require a “Team Approach”

- **Engine Manufacturer**
  - To design the cleanest possible engine (within reasonable cost and performance constraints)
  - EFI, closed-loop system, electronic engine management system

- **Exhaust System Supplier**
  - Muffler design (sound, styling, backpressure)
  - Optimum catalyst positioning

- **Catalyst and Substrate Suppliers**
  - Cost effective catalyst technology for specified operating conditions
  - Proper selection of substrate (size, materials, cell density, etc.)
  - Excellent light-off, high conversion, excellent durability
Comments on Meeting 30K km Durability Requirement

• Required 30K km durability is new for motorcycles
• Automobiles have long had durability requirements in excess of 80K km
• Catalyst development has for over 30 years has focused on improving both the performance and durability of automotive catalysts
• Engelhard leverages advanced automotive catalyst experience and expertise into catalysts for motorcycle applications
• Therefore, meeting a 30k km durability requirement should not be an insurmountable technical problem

Euro-3 Program Results Update

• Euro-3 has been achieved at a number of OEMs
  – Closed-loop engine management systems have been required
  – Higher substrate cell densities have been required, at least 200cpsi and up to 400cpsi, up from typical 100cpsi for Euro-2
  – Larger catalyst volumes have sometimes been needed, up to double that required for Euro-2
  – Higher PM loadings have been required, often more than twice as much as for Euro-2 but increased use of currently lower cost palladium has minimized the cost impact
  – So far there has been no need for extra catalysts to be mounted close to the engine to improve light-off
While requiring technological upgrades in engine and catalyst design, meeting Euro-3 is proving to be achievable using available technology.
Proprietary Duracat™ Screen Catalyst System

- Low cost, ideal for utility engine applications
- Light weight, fast light-off
- Coated on large, flat sheets which can be cut to desired shape
- Excellent adherence of catalyst allows screen to be rolled (shown), bent, or folded without significant catalyst loss
- Has demonstrated excellent customer durability in consumer applications for 125hrs. Recently achieved 300hrs in a professional application
- HC conversion efficiencies demonstrated to over 50%
- Screen geometries and PM loadings can adjusted to achieve desired performance

Conventionally Coated Stainless Steel Screen Prior to Thermal Shock Treatment
Non-Duracat™ Catalyzed Stainless Steel Mesh Shows Considerable Coating Loss after only 10 Minutes Thermal Shock Treatment

Thermal Shock Procedure: **20 cycles** (30 second cycles; 10 total minutes): insert sample into Bunsen Burner flame (ca. 60°C to 900°C); 900°C for 2-3 seconds/cycle; remove from flame and cool with DI water spray; blow with hair dryer

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Duracat™ Screen Prior to Thermal Shock Treatment
Duracat™ Screen Shows Excellent Durability after 5 Hours Thermal Shock Treatment

Thermal Shock Procedure: **600 cycles** (30 second cycles; 5 total hours): insert sample into Bunsen Burner flame (ca. 60°C to 900°C); 900°C for 2-3 seconds/cycle; remove from flame and cool with DI water spray; blow with hair dryer.

Durability Testing of Duracat™ Screen Catalyst

- **Screen specs:**
  - 36mm W x 175 mm L, 12 mesh
  - (2.1mm pitch), 0.71mmD
  - 304SS wire

- **Catalyst:**
  - 0.0234 gPM/part,
  - 2.47Pt/1.33Pd/1Rh

- **Geometry:**
  - Screen formed into 33mm H x 58mm D radial-flow cylinder
Duracat™ Screen Shows Excellent Durability When Aged for 125 hrs on a Consumer Chainsaw Engine Even With High P Oil

![](chart.png)

- Tested on 2-S 42cc consumer chainsaw @ wide-open-throttle and full load

Duracat™ Screen Can Be Cut and Stacked in Modular Fashion to Achieve Desired Conversion Efficiency

Exhaust Flow

Each Piece Approx. 3.0 cm X 3.5 cm
Duracat™ Screen Can Be Cut and Stacked in Modular Fashion to Achieve Desired Conversion Efficiency: Test Results

- Aged on 2-S 50cc blower engine
- Evaluated on 2-S 32cc trimmer engine @ WOT

Duracat™ Screen Catalyst System: Summary

- Demonstrates superior coating adhesion after thermal shock aging when compared to conventionally coated screens
- Has demonstrated up to 300hrs of acceptable catalyst durability in a professional utility engine application
- Experience has shown that screen can be cut to desired shapes, stacked, or rolled into radial flow or heat tube configurations without significant washcoat loss or damage
- Many of the world’s utility engines and mufflers are produced in China and today more than one million small engine mufflers are manufactured annually using Duracat™ screens
- Applications include emission control strategies for small utility engines and heat tubes for 2-wheelers