Comments To The Health Effects Institute Special Committee On Emerging Technologies

Michael P. Walsh
May 2005

Emission Legislation Limits and fuel economy

Light Duty Vehicle NOx Standards (g/km)

Light Duty Vehicle PM Standards (g/km)
Production of Diesel Passenger Cars

### Western Europe

- **Direct Injection**
- **Indirect Injection**

**Exceeded 50% in Oct '04**

### Distribution of certified PM-values of current Diesel Cars

**PM values (mg/km)**

- **EURO 3**: up to 10.0 mg/km
- **EURO 3 + DPF**: up to 12.5 mg/km
- **EURO 4**: up to 5.0 mg/km
- **EURO 4 + DPF**: up to 2.5 mg/km

**PM < 8.5 mg/km**

- To achieve PM < 8.5 mg/km, a filter efficiency typically > 50% is required.

### Cooled EGR and Particulate Reduction

**Hardware Requirements with DPF for Euro 4**

**Euro 3**
- Base engine:
  - Mechanically sound engine
  - Lube oil consumption < 0.1 g/KWh
  - Peak firing pressure potential 200 bar
- Combustion system
  - High EGR tolerance
  - Combustion bowl for low soot in oil
  - Alternative combustion at part load for temperature management

**Euro 4**
- Diesel particulate filter > 79% eff.

**Displacement**: 0.9 - 1.4 liter / cyl.
**Rated speed**: 2200 - 2600 rpm

### Emission Reduction Technology

**EGR + Particulate Reduction with DPF**

- **Advantages**
  - High PM conversion rates
- **Challenges**
  - Regeneration: min. 250°C exhaust gas temperature
  - Low sulfur fuel required to avoid too frequent maintenance due to ash accumulation

**Source**: Johnson Matthey
**Spectacular Filter Damage**

Ring-off-Cracks and Melting of the Cordierite Material

*Source: Johnson Matthey*

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**Ash Plugging of Filter Cells**

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**Cooled EGR and Particulate Reduction**

**Hardware Requirements with POC for Euro 4**

<table>
<thead>
<tr>
<th>Euro 3</th>
<th>Euro 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Displacement</strong></td>
<td>0.9 - 1.4 liter / cyl.</td>
</tr>
<tr>
<td><strong>Rated speed</strong></td>
<td>2200 - 2600 rpm</td>
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<tr>
<td><strong>Base engine</strong></td>
<td></td>
</tr>
<tr>
<td>• Mechanically sound engine</td>
<td></td>
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<tr>
<td>• Lube oil consumption &lt; 0.1g/KWh</td>
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<tr>
<td>• Peak firing pressure potential 200 bar</td>
<td></td>
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<tr>
<td>+</td>
<td></td>
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<tr>
<td>• High performance EGR-system</td>
<td></td>
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<tr>
<td>• Improved vehicle cooling system</td>
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<tr>
<td>• Fully flexible FI with &gt; 1800 bar</td>
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<tr>
<td>• 2-stage turbocharging for &gt; 32 kW/l</td>
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<tr>
<td>+</td>
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<tr>
<td>Combustion system</td>
<td></td>
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<tr>
<td>• high EGR tolerance</td>
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<td></td>
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<tr>
<td>+</td>
<td></td>
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<tr>
<td>Particulate oxidation catalyst &gt; 50%</td>
<td></td>
</tr>
</tbody>
</table>

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**and this is how it starts**
Emission Reduction Technology
EGR + Particulate Reduction with POC

Advantages
- No risk of filter blocking, no active regeneration
- Small packaging volume

Challenges
- Lower conversion rates compared to DPF
- Requires higher fuel injection pressure
- Low sulfur fuel required

Mechanism and Effectiveness:
- Carbon-PM oxidized by NOx being formed in Oxidat
- HC, Sol-PM and CO oxidized in Oxidat
- Conversion Rates (ESC & ETC)
  - Particulates: $\eta_{PMP} = 90\%$
  - Target: $\eta_{PMP} = 70\%$
  - Further development
- Hydrocarbons: $\eta_{HCHC} = 95\%$
- Carbon monoxide: $\eta_{CO} = 95\%$

Source: Emitec GmbH and MAN

Engine Concept Requirements
Hardware Requirements with SCR for Euro 4

Displacement 0.9 - 1.4 litre / cyl.
Rated speed 2200 - 2600 rpm
Specific power 26.4 kW / litre

Base engine:
- Mechanically sound engine
- Lube oil consumption < 0.1g/KWh
- Peak firing pressure potential 135 bar

Euro 3
- No EGR-system
- Fully flexible FIE with > 1600 bar
- Peak firing pressure potential 145 bar
- 4 Valve cylinder head

Advantages
- SCR system > 60%NOx, 50%PM eff.

Challenges
- Urea infrastructure required
- Regeneration: min. 200°C exhaust gas temperature
- Low sulfur fuel required

SCR - Selective Catalytic Reduction

Advantages
- Better fuel economy compared to EGR + part. reduction

Challenges
- Urea infrastructure required
- Regeneration: min. 200°C exhaust gas temperature
- Low sulfur fuel required
Strategies for Euro 5+(?) with After Treatment

Potential of cooled EGR

US-EPA NOx Adsorter Concept
Schematic representation

Comparison of Future Emission Standards on HD vehicles

<table>
<thead>
<tr>
<th></th>
<th>PM</th>
<th>NOx</th>
<th>NMHC</th>
<th>CO</th>
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</thead>
<tbody>
<tr>
<td>Passenger car</td>
<td>0.005</td>
<td>0.08</td>
<td>0.024</td>
<td>0.03</td>
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<tr>
<td>Truck</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light-weight (GVW 1.7t or less)</td>
<td>0.005</td>
<td>0.08</td>
<td>0.024</td>
<td>0.03</td>
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<tr>
<td>Middle-weight (GVW over 1.7t - 3.5t or less)</td>
<td>0.007</td>
<td>0.15</td>
<td>0.024</td>
<td>0.03</td>
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<tr>
<td>Heavy-weight (GVW over 3.5t)</td>
<td>0.01</td>
<td>0.31</td>
<td>0.17</td>
<td>0.22</td>
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</tbody>
</table>

1. Unit: Heavy-weight: g/kWh
2. Except Heavy-weight: g/km
3. Note: Target values of particulate matter are applied only to lean-burn, direct-injection vehicles mounted with storing-type NOx reduction catalyst.

Comparison of PM exhaust emission (JAMA DATA)


<table>
<thead>
<tr>
<th></th>
<th>PM</th>
<th>NOx</th>
<th>NMHC</th>
<th>CO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger car</td>
<td>0.005</td>
<td>N.C.</td>
<td>0.001</td>
<td>0.00</td>
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<tr>
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<td>0.001</td>
<td>0.00</td>
</tr>
<tr>
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<td>N.C.</td>
<td>0.001</td>
<td>0.00</td>
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Emission Reduction Technology (Diesel Vehicles)

<table>
<thead>
<tr>
<th>Technology</th>
<th>2003-04</th>
<th>2005</th>
<th>2009-10</th>
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<tr>
<td>Improvement of combustion chamber and air-intake system</td>
<td>○</td>
<td>○</td>
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<tr>
<td>Improvement of fuel injection system</td>
<td>○</td>
<td>○</td>
<td>○</td>
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<tr>
<td>Cooled EGR</td>
<td>○</td>
<td>○</td>
<td>○</td>
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<tr>
<td>Turbo Charger</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>HCCI(Compression Ignition)</td>
<td>×</td>
<td>×</td>
<td>△</td>
</tr>
<tr>
<td>NOx sensor</td>
<td>×</td>
<td>×</td>
<td>○</td>
</tr>
<tr>
<td>Urea sensor</td>
<td>×</td>
<td>×</td>
<td>○</td>
</tr>
<tr>
<td>Exhaust After-treatment Devices</td>
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<tr>
<td>Oxidation Catalyst</td>
<td>△</td>
<td>○</td>
<td>○</td>
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<tr>
<td>Passive Type Diesel Particulate Filter(DPF)</td>
<td>△</td>
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<td>○</td>
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<tr>
<td>Selective Catalytic Reduction (SCR)</td>
<td>×</td>
<td>△</td>
<td>○</td>
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<tr>
<td>NOx Absorber</td>
<td>×</td>
<td>×</td>
<td>○</td>
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</tbody>
</table>

Note: ○: Prevalent △: Limited use ×: Not Possible
Worldwide Motorcycle Emission Regulations

**Europe**
- **EU II** (2003)
  - ECE40
  - Cold Start
  - HC: 1.0
  - NOx: 0.3
  - CO: 3.0
- **EU III** (2006)
  - ECE40
  - Cold Start
  - HC: 0.8
  - NOx: 0.15
  - CO: 2.0
  - 12,000/24,000 km

**Japan**
- **III Stage** (2008)
  - HC+NOx: 1.0~1.25
  - CO: 1.0~1.25

**China**
- **II Stage** (2004)
  - ECE40
  - HC: 1.2
  - NOx: 0.3
  - CO: 5.5
- **EU II** (2003)
  - ECE40
  - Cold Start
  - HC: 1.0
  - NOx: 0.3
  - CO: 3.0
- **EU III** (2006)
  - ECE40
  - Cold Start
  - HC: 0.8
  - NOx: 0.15
  - CO: 2.0
  - 30,000 km

**Taiwan**
- **II Stage** (2005)
  - IDC Cold Start
  - HC+NOx: 1.5
  - CO: 1.5
- **III Stage** (2008)
  - ECE40
  - Cold Start
  - HC+NOx: 2.0
  - CO: 7.0
  - 15,000 km

- **Developing Countries**

  - **Population**
    - Adopted 70.5%
    - Not Adopted 29.5%
  - **Vehicle Population**
    - Adopted 43.7%
    - Not Adopted 56.3%

- **India**
  - Adopted 65.0%
  - Not Adopted 35.0%

- **Population**
  - Adopted 71.0%
  - Not Adopted 29.0%

- **Vehicle Population**
  - Adopted 59.0%
  - Not Adopted 41.0%


**Developing Countries Which Have Adopted US Or EU Standards For New Vehicles**

**Institution**
-对外合作
-能源基金会
-交通项目
-基础数据
-机动车统计报表
.xls
Vehicle Growth in Beijing is Exploding

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Source: He Kebin

Pollution Shifting From Coal Based To Vehicle Based

Beijing November 2004

Control Measures on Motor Vehicle Pollution

Emission Standards For New Vehicles

<table>
<thead>
<tr>
<th>Category</th>
<th>Before 2000</th>
<th>2000</th>
<th>2001</th>
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<tr>
<td>PC</td>
<td>ECE 1503</td>
<td>EURO I</td>
<td>=</td>
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<td>EURO II</td>
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<td>LDV &amp; LDY</td>
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<td>=</td>
<td>EURO III</td>
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Beijing, Shanghai already Introduced Euro 2 in 2003

New Vehicle Emissions Standards (light duty vehicles)

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<tr>
<th>Country</th>
<th>95</th>
<th>96</th>
<th>97</th>
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<td>Euro 2</td>
<td>Euro 3</td>
<td>Euro 4</td>
<td>Euro 5</td>
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<td>Bangladesh</td>
<td>Euro 2 (under discussion)</td>
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<td>India *</td>
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<td>Taipei, China</td>
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<td>Euro 3</td>
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</tbody>
</table>

*a Entire country
*b Delhi and other cities; Euro 2 introduced in Mumbai, Kolkata and Chennai in 2001; Euro 2 in Bangalore, Hyderabad, Khampur, Pune and Ahmedabad in 2003, Euro 3 to be introduced in Delhi, Mumbai, Kolkata, Chennai, Bangalore, Hyderabad and Ahmedabad in 2005
*c Beijing and Shanghai
*d Gasoline vehicles under consideration
*e for gasoline vehicles
*f for diesel vehicles
*g for all types of diesel vehicles
**New Vehicle Standards in India**

- **Entire Country**
  - Euro 2 – April 2005
  - Euro 3 – April 2010

- **Major Cities**
  - Delhi, Mumbai, Kolkata, Chennai, Bangalore, Hyderabad & Ahmedabad, Pune Surat, Kanpur & Agra Already Euro 2
  - Tighter emission norms for all private vehicles, city public service vehicles and city commercial vehicles
    - Euro 3 From April 2005
    - Euro 4 From April 2010

**India Diesel Fuels Road Map**

- Some parts of Country will not meet 2005 schedule;
- Largest Reliance Refinery Now Making 10 PPM

**Exhaust Emission Standards in Korea**

- **Gasoline Passenger Car**
  - LEV of LEV-1 standard was applied in Jan. 2003.
  - ULEV of LEV-2 standard (of CARB) will be applied from 2006.1 with a phase-in of 25/50/75/100%.

- **Diesel HDV**
  - EURO-3 standard was applied in 2002.7/2003.7.
  - EURO-4 standard will be applied from 2006.10/2008.1.
  - ESC/ETC test mode will be adopted.

- **Diesel Passenger Car**
  - EURO-3 will be applied from 2005.1, but half of the cars will have to install DPF.
  - EURO-4 will start from 2006.

- **Diesel LDT**
  - EURO-3 was applied in 2002.7/2003.7.
  - EURO-4 will be applied from 2006.1/2007.1.
Taiwan New Vehicle Emissions Standards

<table>
<thead>
<tr>
<th>Vehicles</th>
<th>Standards</th>
<th>Effective date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline cars</td>
<td>STAGEⅢ</td>
<td>1/1/1999</td>
</tr>
<tr>
<td></td>
<td>STAGEⅣ</td>
<td>1/1/2007</td>
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<tr>
<td>Diesel cars</td>
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<tr>
<td>Motorcycles</td>
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<td>1/7/2004</td>
</tr>
<tr>
<td></td>
<td>STAGEⅤ</td>
<td>1/1/2007</td>
</tr>
</tbody>
</table>

1. The emission standards of gasoline cars and diesel cars: present-USA standard, STAGEⅣ- EURO IV.
2. After enter the WTO, the emission standard of motorcycle will take the EURO standard or USA standard.

Fuel in Taiwan

The composition and performance standards in fuel

(2) Gradually lower the sulfur content in diesel from 5,000 ppmw in 1989 to 50 ppmw in 2005.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Items</th>
<th>2002</th>
<th>2005</th>
<th>2007</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Benzene (vol%), max</td>
<td>0.8</td>
<td>1.2</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>Sulfur (ppmw), max</td>
<td>180</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RVP (psi), max</td>
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<td>TOXICs (mg/km), max</td>
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<td></td>
<td>Aromatics (vol%), max</td>
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<td></td>
<td>Alkenes (vol%), max</td>
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<tr>
<td></td>
<td>Sulfur (ppmw), max</td>
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<td>Cetane Index, min</td>
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<td>Gasoline</td>
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<td>Aromatics (vol%), max</td>
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<td>Alkenes (vol%), max</td>
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<td>Sulfur (ppmw), max</td>
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<td>Alkenes (vol%), max</td>
<td>18</td>
<td>18</td>
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</tr>
</tbody>
</table>

Brazil

- Passenger Cars & Light Commercial Vehicles
  - Tier 1 Phased in 2005-2007 (40/70/100%)
  - FedLev in 2009
  - No Diesel Cars Allowed
- Heavy Duty Trucks & Buses
  - Euro 3 Phased in 2004-2006
  - Euro 4 in 2009
- Fuels
  - Diesel Fuel S in City from 2000 to 50 in 2005 & to 50 in 2009, on rural areas from 2000 to 30 in 2004 & to 100 in 2008
  - Gasoline S from 1000 to 400 in 2004 & to 80 in 2008
- State of Sao Paulo Gearing Up To Push Sulfur Issue

Mobile Sources Program In Mexico

- Tighten emission limits for new gasoline and diesel vehicles.
  - Gasoline:
    - Tier I first introduced in 1999 (US-EPA-94).
    - Tier II to be introduced in 2006, under discussion.
  - Diesel:
    - EPA-98 currently in place.
    - Standards for new diesel vehicles under discussion.
- Key Issue Is Fuel Quality – Sulfur
- EPA Retrofit Initiative
Africa

*50% of Gasoline Now Lead Free
Most Countries Committed by 2005/6
Sulfur Discussion Beginning
MMT Substitute?

Lead Free Gasoline Worldwide 2004

Global Distribution of Emissions Controls
New Gasoline Cars (000)

Global Distribution of Emissions Controls
Motorcycles
Ultra Low Sulfur Diesel Fuel Is Spreading

Global Distribution of Emissions Controls
Diesel Cars (000)

Global Distribution of Emissions Controls
Heavy Duty Diesel Trucks (000)
Global Trends in Vehicle Kilometers Traveled

Global Road Vehicle Kilometers Traveled

Source: WBCSD

Recent and Projected World Transportation Fuel Demand

Transportation is the Fastest Growing CO₂ Emissions Source

Worldwide Fuel Consumption by Light Duty Vehicle

Source: WBCSD

Problem Could Get Worse Due To High Growth Especially In Asia

Personal transport activity by region

... and even more significant freight transport growth: 2.4 % /year

Problem Could Get Worse
Due To High Growth Especially In Asia

Global Road Vehicle Kilometers Traveled

Source: WBCSD