Diesel Fuel Lubricity
Requirements for Light Duty Fuel Injection Equipment

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Robert Bosch GmbH
This presentation covers the interests of

- Robert Bosch GmbH
- Delphi Diesel Systems
- Denso Corporation
- SiemensVDO Automotive AG
- Stanadyne Automotive Corporation
Our Mission for the Future

Our Mission is to increase the number of Diesel vehicles in the USA especially Passenger Cars + SUVs + Light Duty (LD)

- Build a Cleaner Environment
- Conserve Energy Resources
- Reduce Fuel Consumption / CAFE
- Lower CO₂ Emission

- For Diesel Fuel Injection Equipment (DFIE)
  Lubricity is the most valuable and crucial property
Scope of Presentation

Introduction
Experience in Europe
Comparing USA and Europe

- Vehicles and DFIE
- Survey Data

Requirements

- HFRR method
- Sensitivity of DFIE to HFRR
- Rating Table for Assessed Pump Wear
- Endurance Performance

Data for Diesel Fuels with HFRR between 400 - 650 µm

- Pump Performance: Rotary pumps, Common Rail Systems

Engine Results

Conclusions
A Brief Review

- Sweden introduced sulphur-free fuels in 1990, California followed in 1993 with low-sulphur fuels
  → Failures of fuel-lubricated injection pumps (for passenger and light duty vehicles)
- Lubricity identified as cause
  → Hydroprocessing for desulphurization reduces lubricity enhancing fuel components
- All DFIE manufacturers afflicted
- Process to define wear test method and lubricity limit for fuel spec:
  HFRR (ISO 12156-1, -2, ASTM D-6079)
  → EN 590 et al. Lubricity Limit =460 µm
  SLBOCLE (ASTM D-6078/99)
Experience in Europe

Current Situation in EU

- In Europe 40% of new cars are Diesel vehicles:
  - Passenger and Light Duty vehicles (e.g. SUV)
- EN 590 lubricity spec. (HFRR 460 µm max.) successfully prevents field problems
- Diesel vehicles improve fuel consumption by 30% compared to SI engines
- Diesel vehicles have low fuel consumption (up to 78 mpg)
- Diesel vehicles produce lower CO$_2$ emissions
- Diesel vehicles provide low service costs and high service intervals
- Drivers enjoy driving diesel vehicles due to superior torque characteristics
- Majority of High Pressure DFIE is fuel-lubricated
### Main Differences in Diesel Vehicles

<table>
<thead>
<tr>
<th></th>
<th>Today</th>
<th>Future</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>U.S. / California</td>
<td>EU</td>
</tr>
<tr>
<td><strong>Vehicles</strong></td>
<td></td>
<td></td>
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<tr>
<td>Heavy Duty</td>
<td></td>
<td>Light Duty</td>
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<tr>
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<td>Heavy Duty</td>
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<tr>
<td>Passenger</td>
<td></td>
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<td>Light Duty</td>
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<td></td>
</tr>
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<td></td>
<td></td>
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<tr>
<td><strong>DFIE</strong></td>
<td></td>
<td></td>
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<tr>
<td>Inline pumps</td>
<td></td>
<td>Common Rail</td>
</tr>
<tr>
<td>UIS/UPS</td>
<td></td>
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</tr>
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<td>Common Rail</td>
<td></td>
<td>Rotary pumps</td>
</tr>
<tr>
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<td></td>
<td></td>
</tr>
<tr>
<td><strong>Lubricity requirement</strong></td>
<td>(+)</td>
<td>++</td>
</tr>
<tr>
<td><strong>Lubricity specification</strong></td>
<td>U.S.A.: none</td>
<td>HFRR 460 µm max.</td>
</tr>
</tbody>
</table>
# Survey of U.S.A. Diesel Fuels

## Samples from Summer 2002

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>U.S.A.</th>
<th>Europe (EN 590)</th>
<th>Assessment of U.S.A. Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>kg/m³</td>
<td>813 ... 863</td>
<td>820 ... 845</td>
<td>wide range</td>
</tr>
<tr>
<td>Viscosity</td>
<td>c.St. (40 °C)</td>
<td>2.1 ... 3.2</td>
<td>2.0 ... 4.5</td>
<td>o.k.</td>
</tr>
<tr>
<td>Dist. 95% vol rec.</td>
<td>°C</td>
<td>324 ... 344</td>
<td>&lt; 360</td>
<td>o.k.</td>
</tr>
<tr>
<td>Total Aromatic Cont.</td>
<td>%</td>
<td>16 ... 46</td>
<td>n.a.</td>
<td>many high numbers</td>
</tr>
<tr>
<td>Cetane No.</td>
<td></td>
<td>44 ... 57</td>
<td>&gt; 51</td>
<td>many low numbers</td>
</tr>
<tr>
<td>Sulphur</td>
<td>mg/kg</td>
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<td>42 ... 96</td>
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<tr>
<td>Total Contamination (particulates)</td>
<td>mg/kg</td>
<td>0.8 ... 3.1</td>
<td>&lt; 24</td>
<td>some high numbers</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(EN590 limit too high)</td>
</tr>
<tr>
<td>Lubricity</td>
<td>μm (HFRR 60C)</td>
<td>351 ... 648</td>
<td>&lt; 460</td>
<td>80% of samples &gt; 460 μm</td>
</tr>
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<td>Alcohol</td>
<td>% vol.</td>
<td>&lt; 0.1</td>
<td>n.a.</td>
<td>o.k.</td>
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</tbody>
</table>
ISO 12156-1 Method

Test conditions:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied load</td>
<td>200 g ± 0.01 g</td>
</tr>
<tr>
<td>Stroke length</td>
<td>1 ± 0.02 mm</td>
</tr>
<tr>
<td>Frequency</td>
<td>50 ± 1 Hz</td>
</tr>
<tr>
<td>Test duration</td>
<td>75 ± 0.1 min</td>
</tr>
<tr>
<td>Fluid temperature</td>
<td>60 ± 2 °C</td>
</tr>
<tr>
<td>Fluid volume</td>
<td>2 ± 0.20 ml</td>
</tr>
<tr>
<td>Bath surface</td>
<td>6 ± 1 cm²</td>
</tr>
</tbody>
</table>

→

WS1.4 µm
Sensitivity of DFIE to HFRR

Linear regression:  Pump wear 3.5  ==>  WS1.4 = 454 µm
# Table to Assess Pump Wear

<table>
<thead>
<tr>
<th>Component</th>
<th>Wear rating: 1 – 3.5</th>
<th></th>
<th>Wear rating: 4 – 6</th>
<th></th>
<th>Wear rating: 7 – 10</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Durability + performance = 100 %</td>
<td>Wear rating: 4 – 6</td>
<td>Durability reduced to 20 %</td>
<td>Wear rating: 7 – 10</td>
<td>Durability reduced to 1 %</td>
<td>Immediate failure</td>
</tr>
<tr>
<td></td>
<td>Type of wear</td>
<td>Wear rate</td>
<td>Type of wear</td>
<td>Wear rate</td>
<td>Type of wear</td>
<td>Wear rate</td>
</tr>
<tr>
<td>Cam plate runway</td>
<td>rolling and abrasive</td>
<td>&lt; 1 μm</td>
<td>seizure and fatigue</td>
<td>1 – 30 μm</td>
<td>fatigue</td>
<td>not determinable</td>
</tr>
<tr>
<td>cam plate centre</td>
<td>fretting</td>
<td>1 - 3 μm</td>
<td>fretting</td>
<td>3 - 10 μm</td>
<td>fretting</td>
<td>not determinable</td>
</tr>
<tr>
<td>cam plate claws</td>
<td>fretting</td>
<td>&lt; 10 μm</td>
<td>rolling and fretting</td>
<td>10 - 20 μm</td>
<td>seizure</td>
<td>not determinable</td>
</tr>
<tr>
<td>Roller</td>
<td>rolling</td>
<td>&lt; 1 μm</td>
<td>seizure and fatigue</td>
<td>1 - 5 μm</td>
<td>seizure and fatigue</td>
<td>not determinable</td>
</tr>
<tr>
<td>Roller bolt</td>
<td>rolling</td>
<td>&lt; 1 μm</td>
<td>fretting and seizure</td>
<td>1 - 10 μm</td>
<td>seizure</td>
<td>&gt; 10 μm</td>
</tr>
<tr>
<td>- point of contact to roller</td>
<td>fretting</td>
<td>&lt; 10 μm</td>
<td>fretting</td>
<td>10 - 15 μm</td>
<td>seizure</td>
<td>&gt; 15 μm</td>
</tr>
<tr>
<td>- point of contact to roller ring</td>
<td>fretting</td>
<td>10 - 15 μm</td>
<td>seizure</td>
<td>&gt; 15 μm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel pump</td>
<td>fretting</td>
<td>&lt; 10 μm</td>
<td>fretting</td>
<td>10 - 200 μm</td>
<td>fretting and seizure</td>
<td>not determinable</td>
</tr>
<tr>
<td>- blades</td>
<td>fretting</td>
<td>1 – 2 μm</td>
<td>fretting</td>
<td>2 - 100 μm</td>
<td>fretting and seizure</td>
<td>not determinable</td>
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<tr>
<td>- raceway</td>
<td>fretting</td>
<td>&lt; 10 μm</td>
<td>fretting</td>
<td>10 - 200 μm</td>
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Pump wear must not exceed “green” zone to meet customer expectation.
Durability Performance

Pump Wear vs. Lubricity over Lifetime

- Good lubricity
- Borderline lubricity
- Insufficient lubricity
- Bad lubricity

Wear (µm) vs. Endurance Testing (hrs)

- HFRR: 680 µm
- HFRR: 575 µm
- HFRR: 450 µm
- HFRR: 380 µm

→ New DFIE designed to operate with “blue ---” fuel
VE - Rotary Pump with HFRR 450 µm Fuel

Wear rating = 3.5
Bolts: slight scuffing  Supply pump vanes: increased abrasive wear

→ Fuel represents borderline EU quality
→ Fuel adequate for purpose
VE - Rotary Pump with HFRR 650 µm Fuel

Wear rating = 8
Cam plate: 30 µm    Rollers: Seizure    Bolt: 15 µm    Piston: Broken

- Fuel represents worst case U.S. lubricity
- Fuel unfit for purpose
VP44 - Rotary Pump with **HFRR 400 µm Fuel**

- Fuel represents typical EU quality
- Fuel fit for purpose

**Wear rating = 3.0**
Supply pump, roller shoes, feed pump tooth system, and timing piston: minor polishing
Pump Wear with HFRR Range 400 to 650 µm

VP44 - Rotary Pump with HFRR 650 µm Fuel

Wear rating = 7.0
Supply pump, feed pump tooth system, high pressure piston and vanes: severe wear

- Fuel represents worst case U.S. lubricity
- Fuel unfit for purpose
Pump Wear with HFRR Range 400 to 650 µm

Common Rail System with HFRR 460 µm Fuel

- Fuel represents borderline EU quality
- Fuel adequate for purpose
Pump Wear with HFRR Range 400 to 650 µm

Common Rail System with HFRR 650 µm Fuel

Wear rating = 9.0

- Piston: Seizure
- Piston bottom center: 15 µm
- Bearing shell: Seizure
- Polygon: ≥ 1000 µm

- Fuel represents worst case U.S. lubricity
- Fuel unfit for purpose
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**Engine Results for Light Duty Vehicles**

### NO\textsubscript{x} and PM Reduction with CN 55 and 80 Fuels

#### Test conditions:
- 2.2 l DI engine
- European test cycle; MNEDC (cold test with PI)

#### Chart:
- **NO\textsubscript{x} [g/km]** and **partikulates [g/km]**
- **fuel type**
  - standard Diesel fuel (S<10ppm, CN 55)
  - synthetic Diesel fuel (CN 80)
  - synthetic Diesel fuel + SOI delay (CN 80)
- **consumption [l/100km]**
  - EN 590: 6.20
  - synthetic: 5.80
  - synth. + 2°CA delay: 5.90
  - synth. + 3°CA delay: 5.95
  - synth. + 4°CA delay: 6.00

#### Fuel Consumption:
- EURO III (2000):
  - EN 590: 6.20
  - synthetic: 5.80
  - synth. + 2°CA delay: 5.90
  - synth. + 3°CA delay: 5.95
  - synth. + 4°CA delay: 6.00

- EURO IV (2005):
  - standard Diesel fuel (S<10ppm, CN 55)
  - synthetic Diesel fuel (CN 80)
  - synthetic Diesel fuel + SOI delay (CN 80)
NO$_x$ and PM Reduction with CN 60 Fuels

Test conditions:
- 6 cyl., 2.4 l, swirl chamber engine
- U.S.-FTP75 test
Engine Results for Heavy Duty Vehicles

Better Trade-offs for Soot/ NO$_x$ and Fuel Consumption/ NO$_x$ with CN 52 → 59 Fuels

Test conditions:
1 Cyl. HD engine; $V_d$ ca. 2 l, with EGR
Speed = 1710 rpm, Load = 100%
EGR rate ≤ 18 %
Conclusions

Reasoning for HFRR

- HFRR is an adequate test method
- HFRR provides customer satisfaction
- HFRR 460 µm max. known to prevent field problems
- All high-pressure fuel-lubricated injection systems are exceedingly lubricity-sensitive and require clean fuels (no free water and/or contamination)
- Common-rail and Rotary pumps require the same level of lubricity
- Lubricity specification in ASTM D975 needed ASAP
- Spec. should not exceed HFRR: WS1.4 ≤ 460 µm (ISO 12156-1)
- Bosch and DFIE industry willing to
  - share and validate experience
  - offer more tests and
  - cooperate with regulators (CARB, ...)

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