Influence of regenerative braking on the emission behavior of friction brakes

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1. Methodology
1.1 Regenerative braking

Brake disc/pads tested:
- Left front wheel, cast iron disc (330mm), floating caliper
- Pad materials: ECE (copper-free), NAO (copper-free)

Test procedure of regenerative braking
- Three different types of regenerative braking were investigated

- Influencing the WLTC by regenerative braking
  - Typ 1: 20 single brake events, max. $\Delta_{\text{speed}}$: 34.8km/h, max. $v_{\text{init}}$: 131.3km/h
  - Typ 2: 13 single brake events, max. $\Delta_{\text{speed}}$: 12.5km/h, max. $v_{\text{init}}$: 13.5km/h
  - Typ 3: 5 single brake events, max. $\Delta_{\text{speed}}$: 2km/h, max. $v_{\text{init}}$: 3km/h (no measurable emissions)
1. Methodology
1.2 Test procedure

Potential for regenerative braking systems for different intensities of load

I. WLTC cycle (low intensity)
   a. Step 1: bedding proc. (150x AK-Master sec. 3 + 3x WLTC cycle)
   b. Step 2: 20x WLTC cycle without regenerative braking (reference)
   c. Step 3: 3x20x WLTC cycle under simulation of regenerative braking (typ 1, 2 and 3)

II. AK-Master – pressure series, sec. 4.1 – 4.4 (high intensity)
   • Step 1: run-in procedure (150x AK-Master sec. 3)
   • Step 2: Parameter variation (rot. Speed and brake pressure) without regenerative braking (reference)
   • Step 3: Parameter variation under simulation of regenerative braking (typ 1, 2 and 3)

➤ Focus for the following results: AK-Master sec. 4.3 (120-80km/h)

<table>
<thead>
<tr>
<th>AK-M 4.1</th>
<th>AK-M 4.2</th>
<th>AK-M 4.3</th>
<th>AK-M 4.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 stops</td>
<td>3 stops</td>
<td>3 stops</td>
<td>3 stops</td>
</tr>
<tr>
<td>80-5km/h</td>
<td>80-40km/h</td>
<td>120-80km/h</td>
<td>160-130km/h</td>
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<tr>
<td>IC</td>
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<tr>
<td>15x</td>
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<tr>
<td>80 → 30km/h; 30bar</td>
<td>80 → 40km/h; 30bar</td>
<td>120 → 80km/h; 30bar</td>
<td>160 → 130km/h; 30bar</td>
</tr>
</tbody>
</table>

Bedding procedure / int. conditioning according to AK-Master sec. 3: init. temp. 100°C; pressure: 30bar; Speed range: 80 - 30km / h
1. Methodology
1.3 Measurement devices and testparts

**Measurement devices**

**HORIBA MEXA-2100SPCS**
- CPC (10 - 2.500nm)
  - PNC measuring
- modified sub23nm-version
- Integrated vpr and catalytic stripper

**Dekati ELPI+**
- Electrical low pressure impactor (ELPI)
  - PSD measuring
- Size range: 6–10.000nm

**Sampling system**

- **Constant volume sampling system**
  - Volume flow: 850m³/h
  - High inlet efficiency for particles ≤2.5μm (PN >90%)
  - Isokinetic-sampling (calc. probe diameter)
  - decoupling from the environment (filter)
2. Potential of regenerative braking

2.1 WLTC-Zyklus

Comparison of different friction materials (ECE and NAO) – Mean PNC per cycle

<table>
<thead>
<tr>
<th>ECE</th>
<th>NAO</th>
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<tbody>
<tr>
<td>Reduction potential (mean value of the cycles 16-20)</td>
<td>Typ 1</td>
</tr>
<tr>
<td></td>
<td>65,9%</td>
</tr>
</tbody>
</table>

- Typ 1: High reduction potential of 66% (ECE) to 93% (NAO) under low mechanical and thermal load; NAO: Continuous increase in the mean particle number concentration (Change of tribological contact - Simultaneous change of the coefficient of friction)
- Typ 2: potential up to 99% (max. braking speed: 13.5kph)
- Typ 3: No relevant decelerations / no measurable emissions (max. braking speed: 3kph)
2. Potential of regenerative braking
2.2 AK-Master – pressure series

Comparison of different friction materials (ECE and NAO) – PN per braking operation

- ECE / NAO: high dependence on the rotational speed - nonlinear concentration curve especially for sec. 4.3 + 4.4; different characteristics for the analyzed friction materials
- Potential (typ 3) across all speed ranges, high dependence on the brake pressure recognizable
2. Potential of regenerative braking

2.2 AK-Master – pressure series

Comparison of different friction materials (ECE and NAO)

- ECE: max. PNC for pressures between 40 and 60bar
- NAO: different emission characteristics and potential compared to ECE; high level at low mecha. load (10bar; high level of dependence on braking time); high resistance to high pressure
- Intensity of the number concentration as well as of the potential depending on the coating composition and the existing load parameters (brake pressure / coefficient of friction / braking time, temperature dynamics, rotational speed, ...)

![Regenerative braking (ECE)](image1)

![Regenerative braking (NAO)](image2)
2. Potential of regenerative braking
2.2 AK-Master – pressure series

Comparison of different friction materials (ECE and NAO)

- Reduction of the potential with increasing brake pressure
- ECE: potential up to 80% (typ 3) at low pressure levels (10bar); 30% for typ 1, 40% for typ 2 + 3
- NAO: Reduction potential exists especially at low brake pressure; low potential under high mechanical load (< 20% for brake pressures ≥ 60bar)
2. Potential of regenerative braking

2.3 Temperature behavior

WLTC + AK-Master pressure series

- **WLTC**: Comparable temperature profile for ECE and NAO (NAO: maximum deviation of 7.2°C, average deviation of 3.6°C); low temperature level for typ 1 (slight difference from ambient temperature)
- **AK-M sec. 4.3**: Temperature level (peak temp.) depending on the intensity of regenerative braking; high reduction of the temperature in the friction zone at low mechanical load
2. Potential of regenerative braking

2.4 Particle size distribution (PSD)

WLTC + AK-Master pressure series

- Regenerative braking causes a reduction of the number concentration over the analyzed particle size range (6 - 10,000nm)
- Characteristic of the modal distribution is strongly dependent on the intensity of the load; Reduction of mechanical load / peak temperatures causes a reduction of the number of particles < 100nm (CMD); Lower potential for the formation of volatile components under the influence of recuperation (friction zone temperature)
3. Conclusions / Outlook

- Potential for reducing the number of emitted particles has been demonstrated for different types of regenerative braking; a strong dependence on the brake pad material (ECE/NAO) as well as the loading parameters was proven

- **WLTC cycle:** Reduction potential between 60-90% for typ 1 and up to 99% for typ 2

- **AK-Master pressure series:** Reduction potential is particularly evident for low speed and brake pressure ranges - ECE: between 30% (typ 3, 80bar) and 80% (typ 1, 10 bar);
  - Significant reduction of mechanical load (especially in the low brake pressure range) and peak temperatures and the resulting formation of volatile components

**Influence of regenerative braking:**
- reduction of the number of brake applications
- decreasing of average brake deceleration, application time and brake temperature

**Rust generation cause:**
- Corrosion sticking
- Burnishing wear at disk and pads
- Change of the tribological system (properties of the friction partners and the transfer film)
- Generation of DTV
- Harshness noise (NVH)

- The rust corrosion effect provides additional challenges (future activities)
Acknowledgement

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Thank You for Your Attention!