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Influence of regenerative braking on the emission behavior of friction brakes

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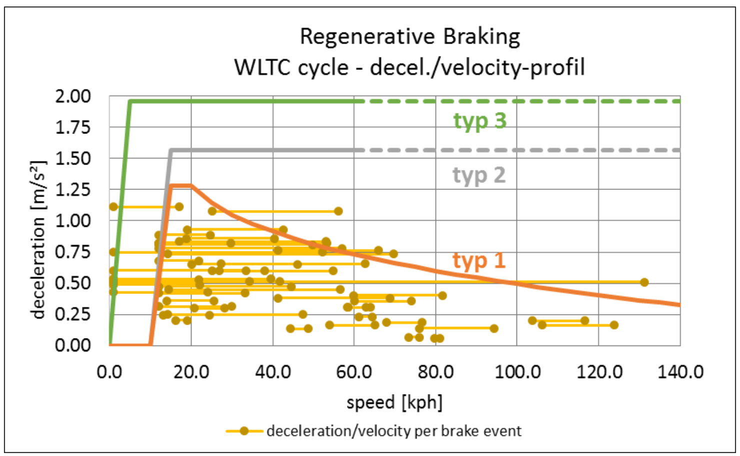
1. Methodology
1.1 Regenerative braking

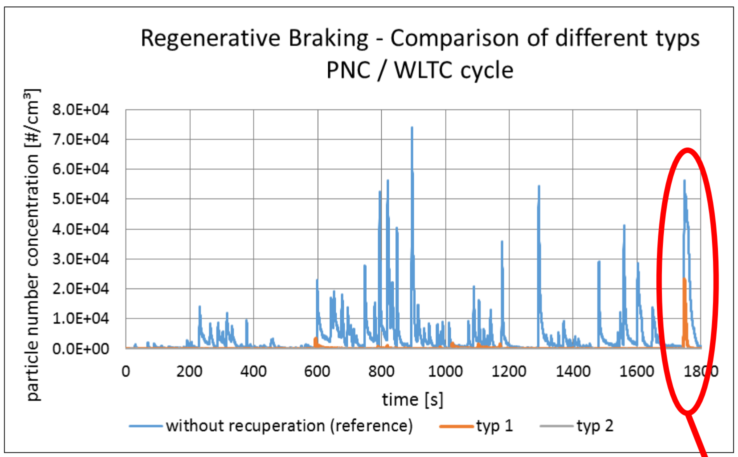
Brake disc/pads tested:

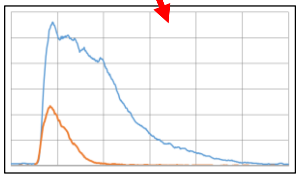
- Left front wheel, cast iron disc (330mm), floating caliper
- Pad materials: ECE (copper-free), NAO (copper-free)

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. Δ_{speed}: 34,8km/h, max. v_{init}: 131,3km/h
  - Typ 2: 13 single brake events, max. Δ_{speed}: 12,5km/h, max. v_{init}: 13,5km/h
  - Typ 3: 5 single brake events, max. Δ_{speed}: 2km/h, max. v_{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)

Bedding procedure 150x 80 → 30km/h; 30bar	Test procedure (low intensity) 20x WLTC cycle

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)**

Bedding procedure 150x 80 → 30km/h; 30bar	**AK-M 4.1** 3 stops 40-5km/h 10-80bar	15x IC	**AK-M 4.2** 3 stops 80-40km/h 10-80bar	15x IC	**AK-M 4.3** 3 stops 120-80km/h 10-80bar	15x IC	**AK-M 4.4** 3 stops 160-130km/h 10-80bar	15x IC

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

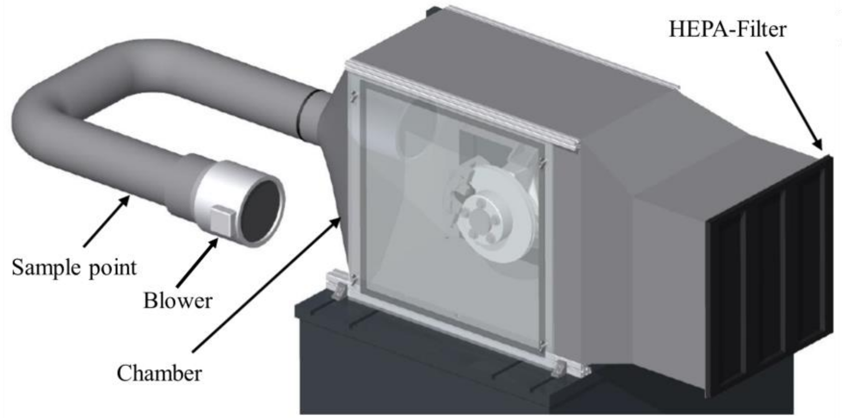
HORIBA MEXA-2100SPCS

- 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

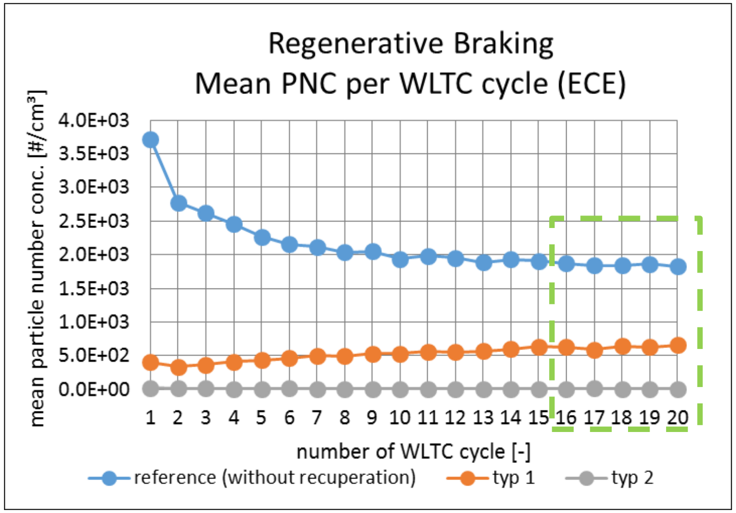


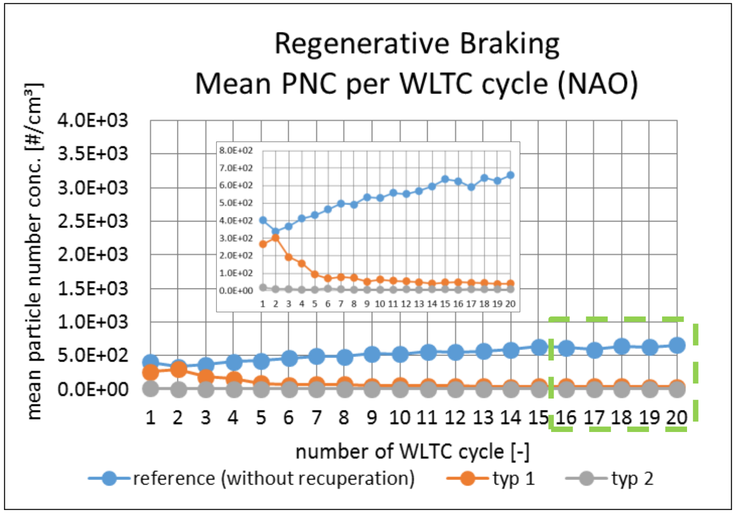
Constant volume sampling system

- 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



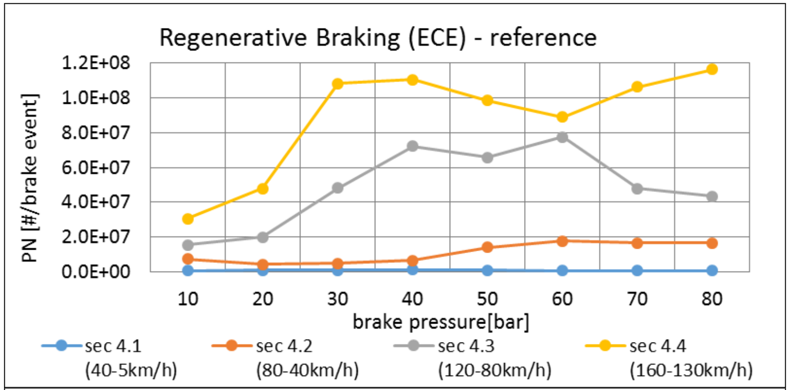


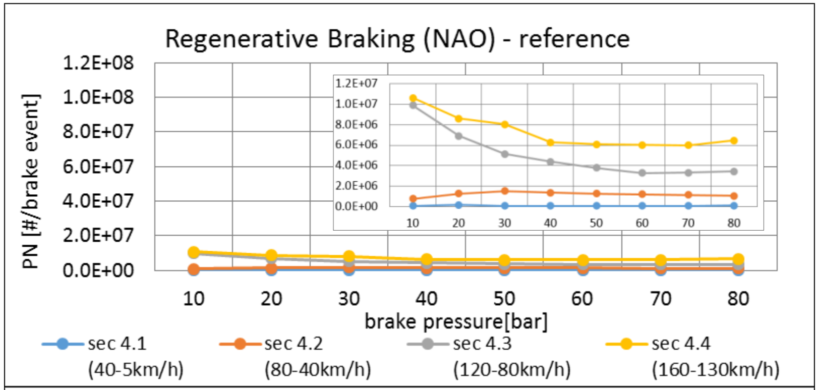
	ECE		NAO	
Reduction potential (mean value of the cycles 16-20)	Typ 1	Typ 2	Typ 1	Typ 2
	65,9%	99,5%	93,0%	98,7%

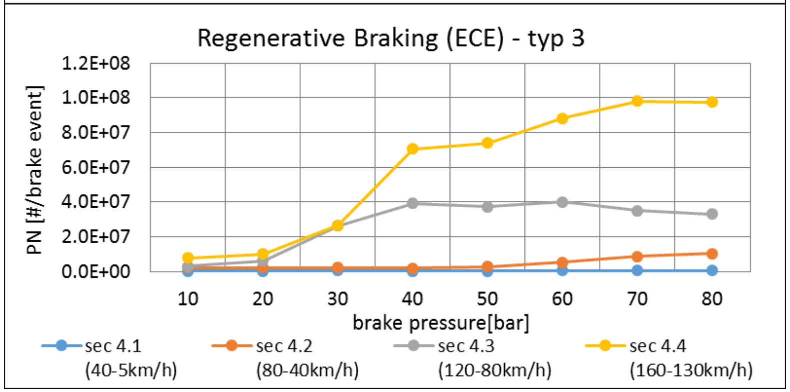
- Typ 1: High reduction potential of 66% (ECE) to 93% (NAO) under low mechanical and thermal load; NAO: Continuous increase in the mean particle number concentration (Change of tribological contact - Simultaneous change of the coefficient of friction)
- Typ 2: potential up to 99% (max. braking speed: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

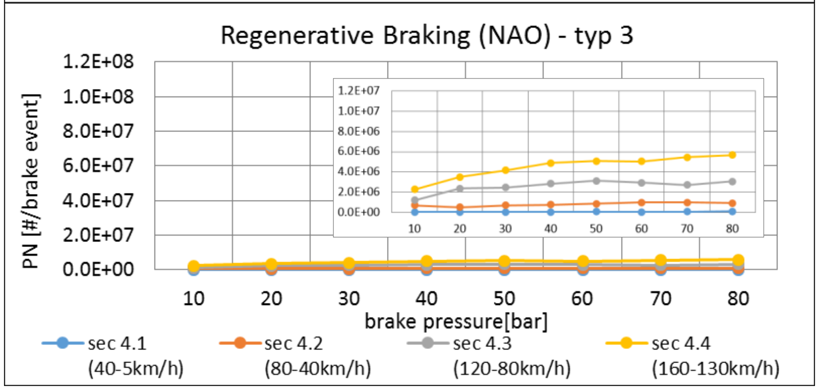
2. Potential of regenerative braking
2.2 AK-Master – pressure series

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







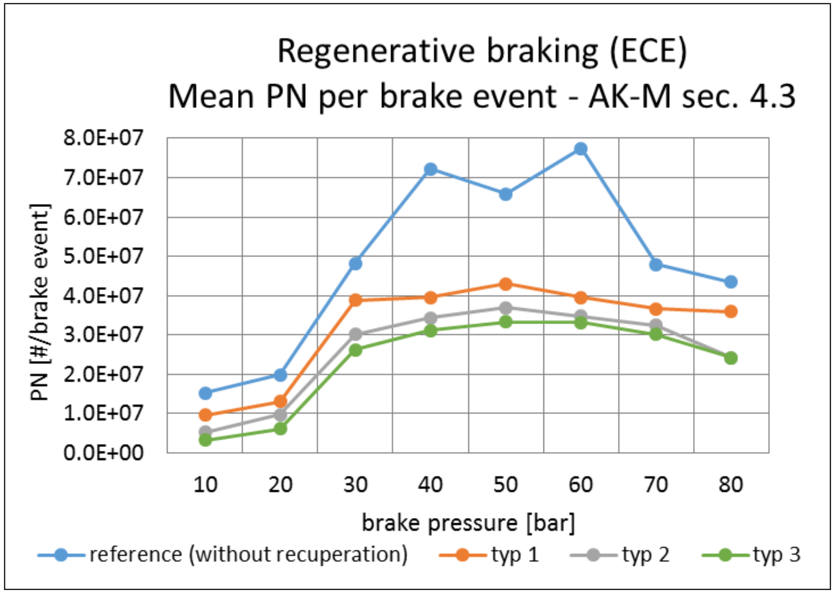


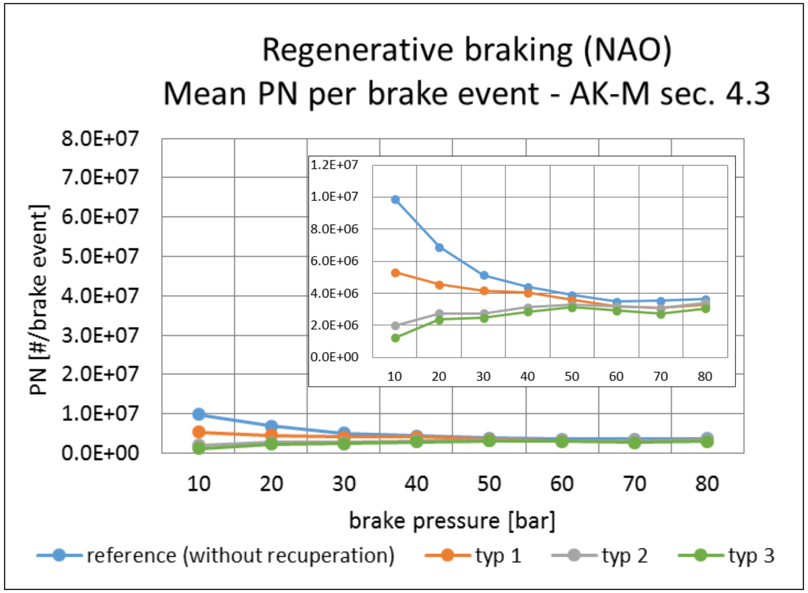
- ECE / NAO: high dependence on the rotational speed - nonlinear concentration curve especially for sec. 4.3 + 4.4; different characteristics for the analyzed friction materials
- Potential (typ 3) across all speed ranges, high dependence on the brake pressure recognizable

2. Potential of regenerative braking

2.2 AK-Master – pressure series

Comparison of different friction materials (ECE and NAO)

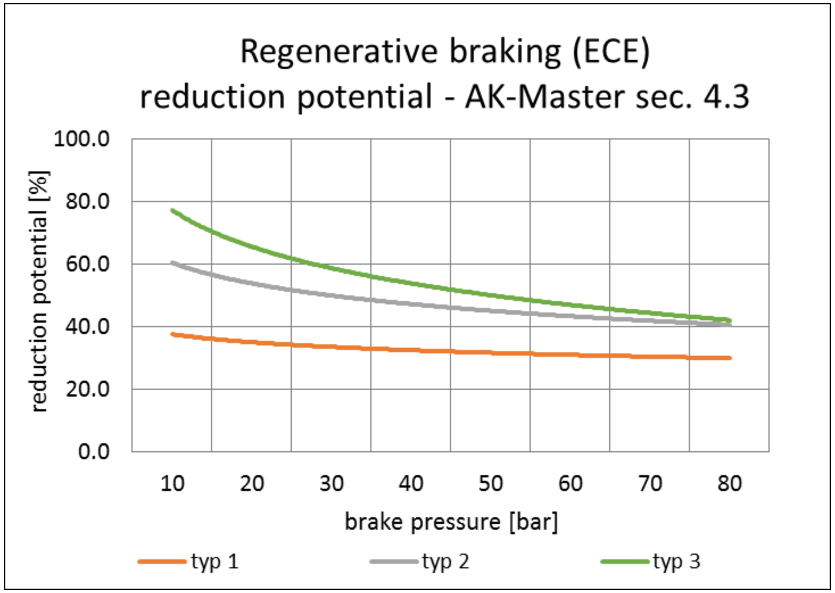


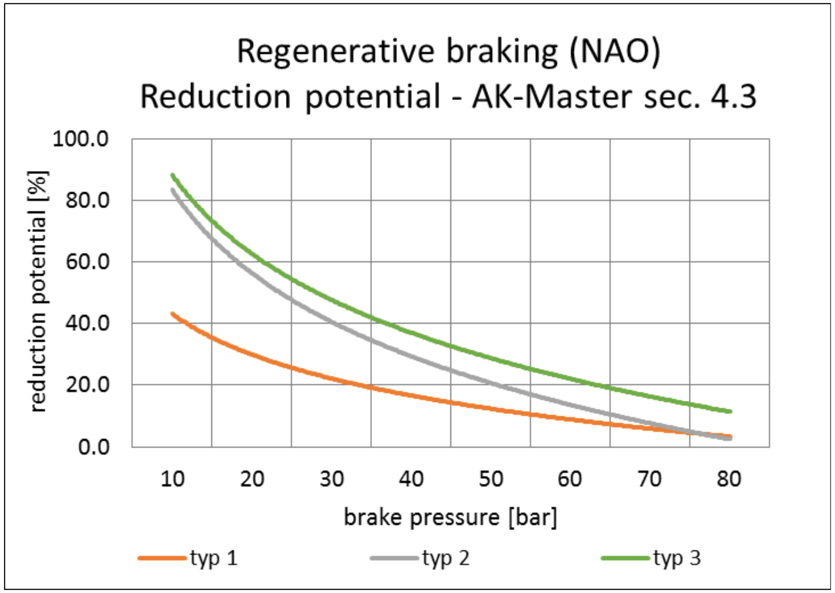


- ECE: max. PNC for pressures between 40 and 60bar
- NAO: different emission characteristics and potential compared to ECE; high level at low mecha. load (10bar; high level of dependence on braking time); high resistance to high pressure
- Intensity of the number concentration as well as of the potential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

2. Potential of regenerative braking
2.2 AK-Master – pressure series

Comparison of different friction materials (ECE and NAO)





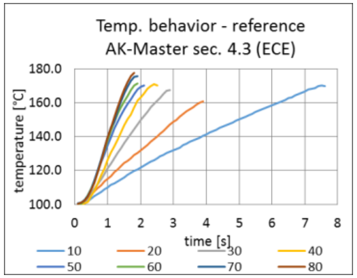
- Reduction of the potential with increasing brake pressure
- ECE: potential up to 80% (typ 3) at low pressure levels (10bar); 30% for typ 1, 40% for typ 2 + 3
- NAO: Reduction potential exists especially at low brake pressure; low potential under high mechanical load (< 20% for brake pressures ≥ 60bar)

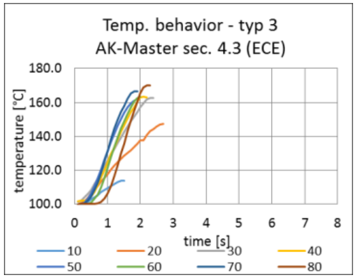
2. Potential of regenerative braking
2.3 Temperature behavior

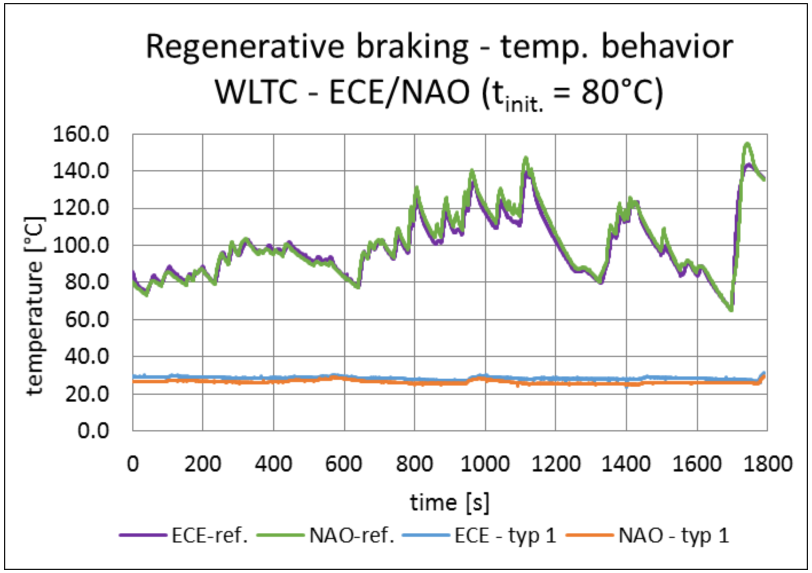
WLTC + AK-Master pressure series

Temperature behavior for ECE friction material:

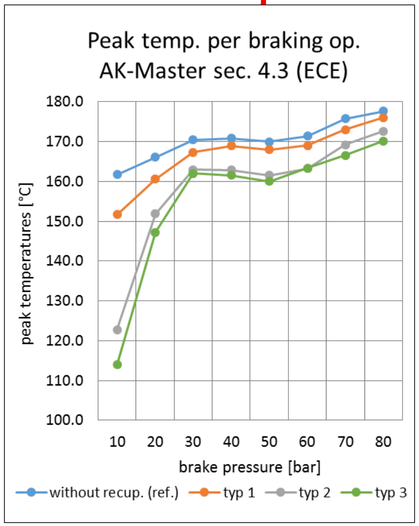
without recup. (ref.) | Typ 3

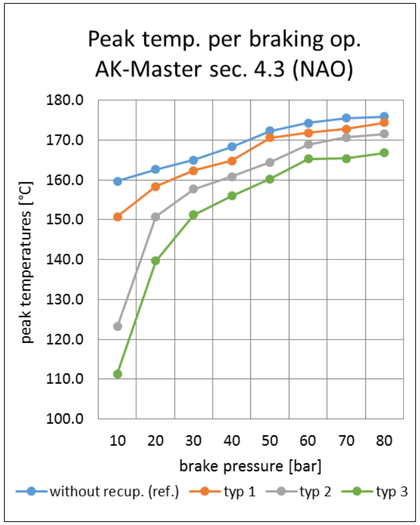






Initial temperature: 100°C

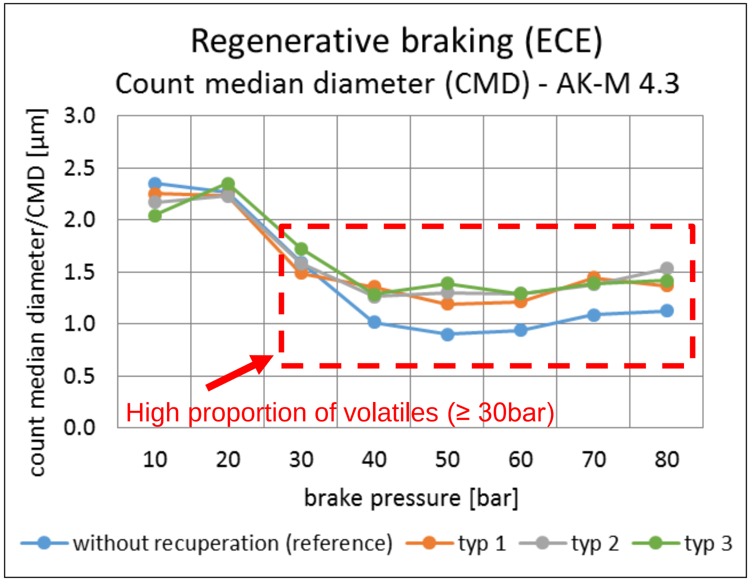


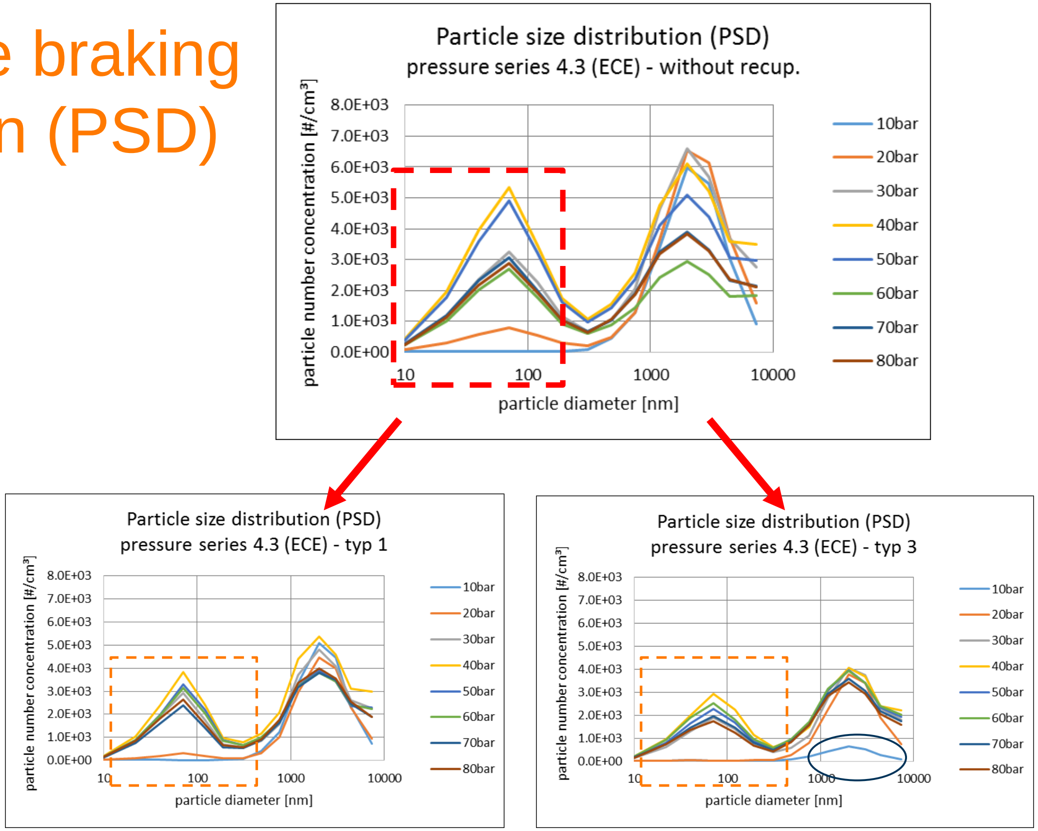


- WLTC: Comparable temperature profile for ECE and NAO (NAO: maximum deviation of 7.2°C, average deviation of 3.6°C); low temperature level for typ 1 (slight difference from ambient temperature)
- AK-M sec. 4.3: Temperature level (peak temp.) depending on the intensity of regenerative braking; high reduction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

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Influence of regenerative braking:	→	Rust generation cause:
• reduction of the number of brake applications • decreasing of average brake deceleration, application time and brake temperature	→	• 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!