

**Dynamometric Investigation on Airborne Particulate Matter from Brake of Automobile:  
Impact of Disc Materials on Brake Emission Factor**

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## 1. Test procedure

The drive sequence of the NOVEL cycle under UN-GTR regulation was employed for the dynamometric test [22] (References [22] are cited in the supplementary materials). The NOVEL cycle has been developed and freely available to the public in Mendeley (WLTP-based Real-World Brake Wear Cycle, <https://data.mendeley.com/datasets/dkp376g3m8/1>). 10 trips with 303 stops in 4.5 h and 192 km are included in the cycle. Average vehicle speed of 44 km/h with maximum speed of 133 km/h. Deceleration rates of 0.5 - 2.2 m/s<sup>2</sup> are applied (mean value of 1.0 m/s<sup>2</sup>). Initial temperature was 40°C before trip 1 (disc) and then controlled on the basis of travel time. Soaking condition is 20°C, 50% RH, 0 kph with cooling air flow.

To determine the appropriate cooling airflow for temperature control, (WL<sub>n</sub>/DM) ratio for our brake dynamometer was determined using a nominal wheel load (WL<sub>n</sub>) to disc mass (DM) group [S1]. Embedded thermocouple was used for the measurement of the brake disc temperature. The WL<sub>n</sub>/DM ratio is calculated by dividing the WL<sub>n</sub> (kg) with the pre-test disc mass (kg). Our WL<sub>n</sub>/DM groups are classified as Group 3 (65 < WL<sub>n</sub>/DM ≤ 85) according to defined WL<sub>n</sub>/DM ratio.

The target values and allowed tolerances for three temperature-related parameters (T<sub>avg</sub>, IBT, FBT) have been defined as follows, against which the cooling adjustment was performed during our tests. For our tests, target temperatures and tolerances are ≥60 °C, 80 ± 20 °C, and 125 ± 30 °C for T<sub>avg</sub>, IBT, FBT, respectively.

- (1) Average brake temperature over Trip #10 of the WLTP-Brake Cycle (T<sub>avg</sub>);
- (2) Average initial brake temperature of selected brake events (IBT);
- (3) Average final brake temperature of selected brake events;

(4) The brake events referred to (2) and (3) are #46, #101, #102, #103, #104, and #106 from Trip #10 of the WLTP-Brake Cycle.

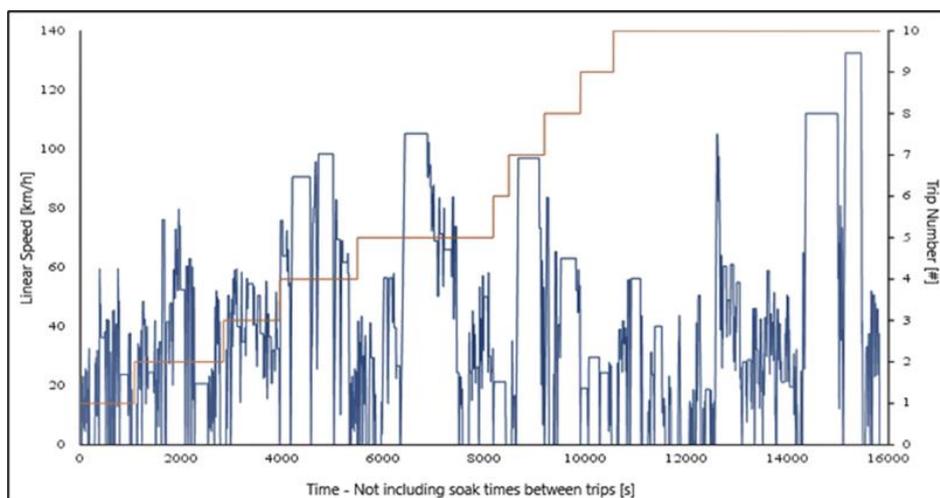


Figure S1. Time-resolved vehicle speed for the NOVEL brake Cycle. Soak times between trips are not included.

Table S1. Time table of NOVEL brake cycle

Trip No.	Trip 1	Trip	Trip 3	Trip 4	Trip 5	Trip 6	Trip 7	Trip 8	Trip 9	Trip 10
<b>Travel time(sec)</b>	1070	2835	3947	5484	8175	8483	9188	9899	10554	15826
<b>Soak time(min)</b>	-	36	180	24	60	360	12	600	48	900
<b>Braking</b>	29	42	28	18	49	2	6	8	7	114

## 2. PM measurement

The particle mass concentration was calculated from the amount of scattered light according to Eq. 1 [7,21] (References [7,21] are cited in the supplementary materials). First, particle numbers in separate 32 channels of OPC are collected as a time-series (1-1800s). Then, particle mass for each channel is calculated from the number values assuming uniform density and spherical shape, volume:  $4\pi/3*(d_i/2)^3$ , at each measurement time. The parameter  $d_i$  represent a diameter of particle collected in each channel. Finally, total mass emission factor was calculated from the summation of particle mass for total measurement period (1-1800s).

Density was set to be calibrated value for brake wear particulate using gravimetric method [21]. Previous studies showed that calibration factor of  $\sim 6$  was used when the detector calibrated according to Arizona Road dust (SAE J726) that has a different composition and light scattering characteristics [S2,7].

$$BEF(mg/km) = \sum_{i=1}^{31} PN * C * K * \rho * \pi * \frac{d_i^3}{6} * f / l \quad (1)$$

-PN : Number concentration of particle emitted (#/L)

-  $l$  : WLTC driving distance (23.27 km)

-  $C$  : detector flow rate (L/min), 1.2

-  $\rho$  : density (g/cm<sup>3</sup>), 5

-  $K = (R/r)^2$  : duct diameter correction factor, R: duct diameter, r: detector line diameter

-  $f$  : scale dynamometer correction factor, front brake area correction factor \*2 + rear brake area correction factor \* 2

-  $d_i$  : average diameter of  $i^{\text{th}}$  channel ( $\mu\text{m}$ )

### 3. Friction Materials

Low-steel (L/S) and non-steel (N/S) friction materials, formulated with varied lubricants and abrasive, were tested for the front brake assembly of a typical medium-size passenger car. The L/S materials consisted of steel fiber, abrasives (SiC, Al<sub>2</sub>O<sub>3</sub>, and ZrSiO<sub>4</sub>), friction modifiers (Fe<sub>3</sub>O<sub>4</sub>, MgO, Iron chromite), lubricants, filler, and resin binder. The formulation of the N/S friction material was very different from L/S, using aramid pulp as reinforcement fiber, abrasives (ZrO<sub>2</sub>, ZrSiO<sub>4</sub>), potassium titanate, filler (BaSO<sub>4</sub>), and lubricant

(graphite). The N/S formulation is a typical one for Cu-free non-steel friction materials using aramid fiber as a reinforcement.

Table S2. Formulation of Non-steel and Low-steel friction materials.

	<b>Non-steel</b>	<b>Low-steel</b>
<b>Fiber</b>	10(aramid)	20(steel)
<b>Reinforcement</b>	10	-
<b>Abrasive</b>	10	20
<b>Friction modifier</b>	20	10
<b>Lubricant</b>	5	10
<b>Filler</b>	30	20
<b>Additive</b>	5(friction dust)	10(Cokes)
<b>Binder</b>	10	10

4. Surface coating of disc rotors

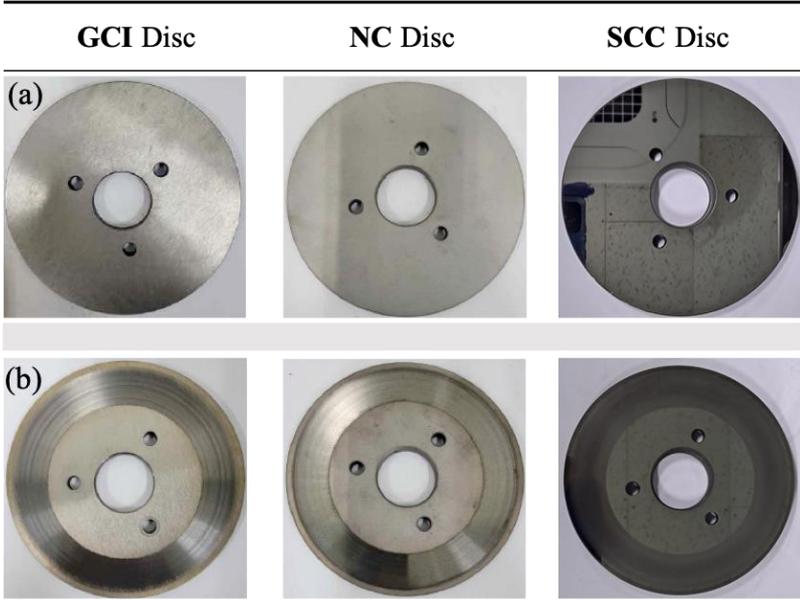


Figure S2. Images of the GCI, NC and SCC discs (a) before dynamometric test and (b) after dynamometric test.

**5. EDS analysis result of collected PM**

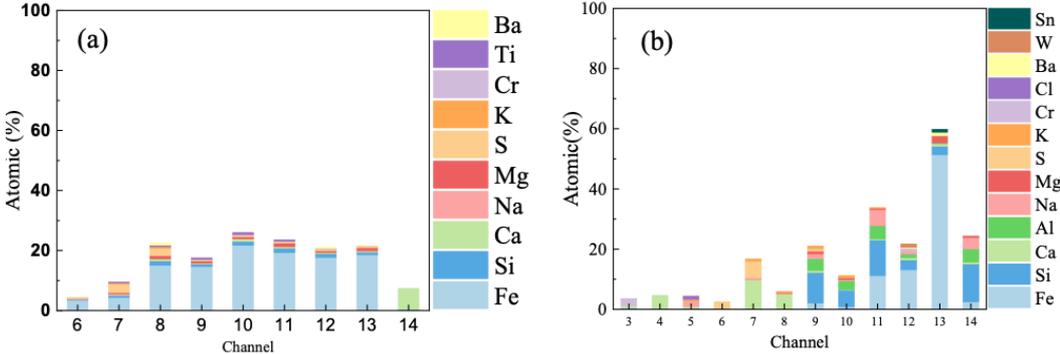


Figure S3. EDS analysis results of airborne PM for (a) the FC170 disc and (b) the SCC disc according to ELPI channel, which is related to the size of the PM.

**6. PSD analysis result by ELPI+**

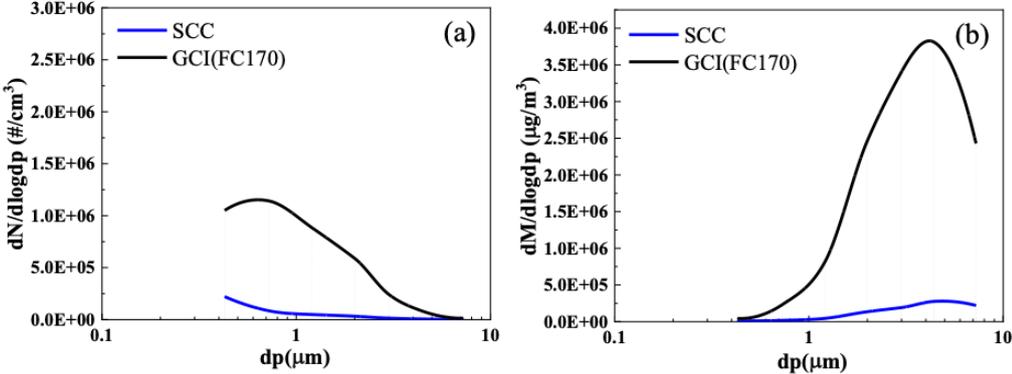


Figure S4. Particle size distribution (PSD) curves of airborne PM emissions, measured by ELPI+ device, for L/S friction materials based on (a) particle number and (b) particle mass.

## 7. References

(S1) PMP-Group Particle Measurement Program (PMP) of the United Nations Working Party on Pollution and Energy (UNECE-GRPE), UN GTR No.24 – Laboratory Measurement of Brake Emissions for Light-Duty Vehicles.  
<https://unece.org/transport/standards/transport/vehicle-regulations-wp29/global-technical-regulations-gtrs>

(S2) zum Hagen, F.H.F.; Mathissen, M.; Grabiec, T.; Hennicke, T.; Rettig, M.; Grochowicz, J.; Vogt, R.; Benter, T. Study of brake wear particle emissions: impact of braking and cruising conditions. *Environ. Sci. Technol.* **2019**, 53, 5143–5150.