Proposal for a new UN GTR on Laboratory Measurement of Brake Emissions for Light-Duty Vehicles

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**I. Statement of Technical Rationale and Justification**

**A. Introduction**

As exhaust emissions reduce, relative contributions of non-exhaust particulate matter increase. Vehicle manufacturers have strong interest to harmonise brake emissions test and performance. The United Nations Global Technical Regulation (UN GTR) proposal uses the Worldwide harmonized Light vehicle Test Procedure (WLTP) for Light-Duty Vehicles (LDV). This UN GTR does not define emissions limit values. According to the 1998 UN ECE agreement this UN GTR applies to vehicles, conditions, and equipment under its formal scope. (LDV up to 3500 kg). This version does not apply to off-road, special purpose, or heavy-duty vehicles. Contracting parties may apply this UN GTR to brake emissions testing with different types of friction materials or mating parts.

**B. Procedural background and future development**

2013

Informal Working Group on Particle Measurement Programme (IWG on PMP) to investigate need to include brake, tyre, or road wear. GRPE-69-23 to set “normal” driving conditions on a novel test cycle for LDV. From AC.3: literature survey, knowledge gaps, establish group of experts, analyse WLTP database, consider suitable testing approach (fully-enclosed brake dynamometer selected).

2016

From AC.3: develop test procedure for sampling and assessing brake wear particles for mass and number: develop and validate novel test cycle, methodologies for particle generation and sampling, instrumentation for measurement and characterization. Create Task Force (TF1) for test cycle and Task Force (TF2) for methodology and instrumentation for brake wear particles.

2016-2019

Selection of brake test rig methodology, agreement to measure PM$_{2.5}$, PM$_{10}$ and PN > 10 nm. TF1 develops and publishes the first Interlaboratory Study (ILS-1) for the WLTP-Brake cycle for test cycle with eight labs (EU and United States). Analysis of existing methods and setups for sampling and measurement; including the need to define their minimum specifications and requirements.

2019-2020

Validation of proposed methodology; update GRPE from TF1 to apply measurement and characterisation of brake emissions on a brake dynamometer, how to address future technologies. From AC.3: consider use of proposed method as regulatory tool. Request to IWG on PMP to look into changes to extend method to all existing technologies and other vehicle categories.

2021

Ideal scheme to regulate brake emissions for ICE LDV, how to handle HEVs and PEVs, possible approaches for heavy-duty vehicles. EU, UK, and Japan obtained authorization from AC.3 to develop new UN GTR on brake PM and PN for all types of LDV. A new TF3 organized and executed ILS-2 with 16 labs (EU, United States, and Japan) to verify feasibility, applicability, repeatability, reproducibility, and prepared recommendations to TF2. Launch of TF4 to investigate and select methodology for non-friction braking and share coefficients.

**C. Background on the technical work of the PMP**

The proposed UN GTR provides information necessary to measure brake emissions in a laboratory, including: references, definitions, and terminology, general requirements and capabilities of test setup, WLTP-Brake cycle, cooling airflow adjustment, bedding, and emissions measurement sections, minimum requirements to report results and metrics. Future work to expand this UN GTR might address (a) real-world cycle for laboratory use, (b) adaptations for new technologies, and (c) brake emissions for heavy duty vehicles.

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**TF1** - WLTP-Brake cycle ILS-1 (8 labs)  
**TF2** - PM & PN setup and measurements  
**TF3** - emissions measurement validation and ILS-2 (16 labs)  
**TF4** - methodology for non-friction braking and (amendments) braking share coefficients

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II. Text of the Global Technical Regulation (GTR)

1. Purpose
Provide a worldwide harmonised methodology for the measurement of brake wear particulate matter and particle number emissions from brakes used on Light-Duty vehicles.

Define the test cycle, minimum system requirements, test conditions, and equipment preparation to execute the WLTP-Brake cycle using brake dynamometers.

Provide requirements for the design and set up of test systems to measure brake emissions, including requirements on calibration and validation of test equipment.

2. Scope and application
Applies to:
- vehicles using some type of mechanical braking, using a combination of dry friction materials and a mating brake disc or brake drum;
- category 1-1 and category 2 vehicles with a fully laden mass below 3500 kg.

The Contracting Parties (countries) shall make a decision about the applicability of this UN GTR to Small Volume Manufacturers for their jurisdiction.

5. General requirements
5.1. Compliance Requirements against the regional emission limits as defined by each Contracting Party by testing the worst-performing representative of a brake family.

5.2. Brake Family
5.3. Rounding Requirements
- at least six significant, or all available digits;
- No rounding of intermediate results;
- Match number of decimal places in Paragraph 13.

6. General Overview
6.1. Test sections

7. Test system: layout, cooling system, dyno controls, brake enclosure, and sampling system

8. Test preparation: input parameters, setup, temperature measurements, and brake positioning

9. WLTP-Brake cycle: ability to execute test cycle and meet quality controls

10. Brake cooling: adjust cooling airflow and meet temperature metrics

11. Brake bedding: complete five WLTP-Brake cycles with correct IBTs, and meet quality controls

12. Brake emissions measurements: complete one WLTP-Brake cycle (PM, PN, and mass loss) and meet quality controls

13. Test results: report test conditions, emissions factors, event-based, time-based, mass loss, and testing parameters

Table 3.1: Default temperature metrics and tolerances for brakes during Test 411 of the WLTP-Brake cycle

<table>
<thead>
<tr>
<th>Group</th>
<th>AT1 (A)</th>
<th>AT2 (A)</th>
<th>AT4 (B)</th>
<th>AT5 (B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>±10 °C</td>
<td>±10 °C</td>
<td>±10 °C</td>
<td>±10 °C</td>
</tr>
<tr>
<td>2</td>
<td>±10 °C</td>
<td>±10 °C</td>
<td>±10 °C</td>
<td>±10 °C</td>
</tr>
<tr>
<td>3</td>
<td>±10 °C</td>
<td>±10 °C</td>
<td>±10 °C</td>
<td>±10 °C</td>
</tr>
</tbody>
</table>

PM$_{2.5}$ EF

PM$_{10}$ EF

TPN10 EF

SPN10 EF

Mass loss

Table 3.2: Default temperature metrics and tolerances for brakes during Test 411 of the WLTP-Brake cycle

10 - Cooling adjustment

11 - Bedding

12 - Emissions Measurements

14 - Calibration and Ongoing Quality Controls
5.2. Brake Family

5.2.1. Characteristics of Brake Emissions Families

All vehicle types independent of their electrification grade may be part of one brake emission family. Only vehicles that feature an identical brake assembly with respect to the characteristics listed in (a)-(c) may be part of the same brake emissions family:

(a) Type of caliper (floating or fixed caliper, number and size of pistons, type of retraction elements);

(b) Type of brake: disc (friction surface, coating, single, dual, ventilated, solid, dimensions, mass) or drum-backplate assembly (friction surface, simplex, duplex, dimensions, mass);

(c) Type of friction material: pad (friction surface, size, shape, material, backing plate) or shoe (friction surface, size, design, material, backing plate).

5.2.2. Brake Emissions Family Parent

The product of the friction braking share coefficient and test wheel load shall be used only to identify the brake emissions family parent and not for testing the brake assembly.

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3. Definitions (subset) – ECE/TRANS/WP.29/GRPE/2023/4 V6 CHEAT SHEET


3.1.9. “Vehicle test mass” in running order + optional equipment +...

3.1.10. “Road loads” total load to move the vehicle on a level and smooth road at constant speed. fixed as 13% of vehicle test mass.

\[ T_L = f_o + f_1 \cdot V + f_2 \cdot V^2 = 13\% \times WL_B \]

3.1.25. “Average by distance”
\[ \frac{(m_1 \times d_1 + m_2 \times d_2 + m_3 \times d_3 + \ldots)}{D} \]

3.1.26. “Average by time”
\[ \frac{(m_1 \times t_1 + m_2 \times t_2 + m_3 \times t_3 + \ldots)}{T} \]

3.4.7. “Brake acceleration event” period during which the linear speed increases at a known rate.
3.4.8. “Brake cruising event” period during which the (non-zero) linear speed is constant.
3.4.9. “Brake dwell event” measurable and predictable brake pause at zero speed during the cycle.
3.4.10. “Brake deceleration event” period during which the linear speed decreases at a known rate.
3.4.11. “Deceleration rate” total rate of reduction in the linear speed from the service brake, road loads, and non-friction torque from the electric machine.

\[ \Delta \frac{v}{\Delta t} \]

3.5.5. “Solid particle number emissions” means the number of solid particles emitted from the brake under testing. Volatile Particle Remover per par. 12.2.

https://www.mdpi.com/2624-8921/2/2/19/htm

3.6.6. “Response time” […] Difference in time from the reference point to the measurement system.

https://wiki.unece.org/display/trans/UNR+RDE

3.7.4. “Category of propulsion energy converter”

https://www.mdpi.com/2624-8921/2/2/19/htm

(4) Visit https://unece.org/sites/default/files/2023-01/GRPE-87-40e_clean.pdf for complete proposal
### 4.1. Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM</td>
<td>Disc mass before testing</td>
<td>kg</td>
</tr>
<tr>
<td>FAF</td>
<td>Front axle brake force distribution</td>
<td>%</td>
</tr>
<tr>
<td>FBT</td>
<td>Final brake temperature at the end of the brake event</td>
<td>°C</td>
</tr>
<tr>
<td>ICE</td>
<td>Internal combustion engine</td>
<td>-</td>
</tr>
<tr>
<td>IR</td>
<td>Isokinetic ratio</td>
<td>-</td>
</tr>
<tr>
<td>NOVC-HEV</td>
<td>Not off-vehicle charging hybrid electric vehicle</td>
<td>-</td>
</tr>
<tr>
<td>OVC-HEV</td>
<td>Off-vehicle charging hybrid electric vehicle</td>
<td>-</td>
</tr>
<tr>
<td>PEV</td>
<td>Pure electric vehicle</td>
<td>-</td>
</tr>
<tr>
<td>PND1</td>
<td>Primary particle number diluter</td>
<td>-</td>
</tr>
<tr>
<td>PND2</td>
<td>Secondary particle number diluter</td>
<td>-</td>
</tr>
<tr>
<td>PCRF</td>
<td>Particle concentration reduction factor</td>
<td>-</td>
</tr>
<tr>
<td>PM</td>
<td>Particulate matter</td>
<td>mg</td>
</tr>
<tr>
<td>PM2.5</td>
<td>Final PM2.5 emission factor</td>
<td>mg/km</td>
</tr>
<tr>
<td>PM10</td>
<td>Final PM10 emission factor</td>
<td>mg/km</td>
</tr>
<tr>
<td>PN</td>
<td>Particle number</td>
<td>#</td>
</tr>
<tr>
<td>PNC</td>
<td>Particle number counter</td>
<td>-</td>
</tr>
<tr>
<td>RAF</td>
<td>Rear axle brake force distribution</td>
<td>%</td>
</tr>
<tr>
<td>REESS</td>
<td>Rechargeable electric energy storage system</td>
<td>-</td>
</tr>
<tr>
<td>SPN10</td>
<td>Final SPN10 emission factor</td>
<td>#/km</td>
</tr>
<tr>
<td>TPN10</td>
<td>Final TPN10 emission factor</td>
<td>#/km</td>
</tr>
<tr>
<td>VPR</td>
<td>Volatile particle remover</td>
<td>-</td>
</tr>
<tr>
<td>WLTP</td>
<td>Worldwide harmonized light vehicle test procedure</td>
<td>-</td>
</tr>
</tbody>
</table>

### 4.2. Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{1,4}$</td>
<td>Metrics for target temperatures</td>
<td>°C</td>
</tr>
<tr>
<td>$B_{1,4}$</td>
<td>Metrics for dynamometer temperatures</td>
<td>°C</td>
</tr>
<tr>
<td>$C_{1,4}$</td>
<td>Metrics for the temperature difference between target and dynamometer</td>
<td>°C</td>
</tr>
<tr>
<td>$d_i$</td>
<td>Sampling tunnel inner diameter</td>
<td>mm</td>
</tr>
<tr>
<td>$d_n$</td>
<td>Sampling nozzle inner diameter (applies to both PN and PM)</td>
<td>mm</td>
</tr>
<tr>
<td>$d_p$</td>
<td>Sampling probes inner diameter (applies to both PN and PM)</td>
<td>mm</td>
</tr>
<tr>
<td>$f_d$</td>
<td>PCRF for each particle of electrical mobility diameter $d_i$</td>
<td>-</td>
</tr>
<tr>
<td>$i_1$</td>
<td>Brake test inertia</td>
<td>kg·m²</td>
</tr>
<tr>
<td>$M_{tot}$</td>
<td>Vehicle test mass to simulate on the dynamometer</td>
<td>kg</td>
</tr>
<tr>
<td>$N_Q$</td>
<td>Average normalised cooling airflow</td>
<td>Nm³/h</td>
</tr>
<tr>
<td>$N_{QPM2.5}$</td>
<td>Average normalised PM2.5 sampling flow</td>
<td>l/min</td>
</tr>
<tr>
<td>$N_{QPM10}$</td>
<td>Average normalised PM10 sampling flow</td>
<td>l/min</td>
</tr>
<tr>
<td>$N_{QPM10-set}$</td>
<td>Nominal (or set) PM10 sampling flow</td>
<td>l/min</td>
</tr>
<tr>
<td>$N_{QPM2.5-set}$</td>
<td>Nominal (or set) PM2.5 sampling flow</td>
<td>l/min</td>
</tr>
<tr>
<td>$N_{QPM2.5}$</td>
<td>Average normalised and PCRF-corrected SPN10 concentration</td>
<td>#/Nm³</td>
</tr>
<tr>
<td>$N_{QPM10}$</td>
<td>Average normalised and PCRF-corrected TPN10 concentration</td>
<td>#/Nm³</td>
</tr>
<tr>
<td>$T_{brake}$</td>
<td>Brake (disc/drum) temperature</td>
<td>°C</td>
</tr>
<tr>
<td>$T_{brake-avg}$</td>
<td>Time-averaged brake torque</td>
<td>N·m</td>
</tr>
<tr>
<td>$W_f$</td>
<td>Specific friction work</td>
<td>J/kg</td>
</tr>
<tr>
<td>$W_{f,avg}$</td>
<td>Buoyancy-corrected filter mass</td>
<td>mg</td>
</tr>
</tbody>
</table>

7. Test System Requirements

S2 — Automation, control, and data acquisition system
Perform all the functions that enable the brake emissions test.
Accelerate, maintains constant speed, and modulates the frictional torque during deceleration events
Provide an interface to the operator, store the data from the test, and handle the interfaces with other systems in the testing facility
Be capable of using active torque control on the electric motor to increase or decrease the total effective test inertia during deceleration events.
The software that operates the test system shall be capable of performing at least the following functions:
  • Execute the driving cycle automatically by operating all the closed-loop processes (mainly for brake controls, cooling air handling, and emissions measurements instruments)
  • Continuously sample and record data from all relevant sensors
  • Monitor signals, messages, alarms, or emergency stops from the operator and systems connected to the test system

S1 — Brake dynamometer
Technical system that provides the controlled kinetic energy to the brake under test. It primarily transforms rotational kinetic energy into thermal energy.
(a) A variable-speed electric motor to accelerate or keep the rotational speed constant. It also modulates the test inertia in real driving conditions and simulates non-friction braking;
(b) A servo controller (hydraulic or electric) to actuate the brake under testing;
(c) A mechanical assembly to mount the brake under testing, allow free rotation of the disc or drum, and absorb the reaction forces from braking;
(d) A rigid structure to mount all the mandatory subsystems. The structure shall be capable of absorbing the forces and torque generated by the brake under testing;
(e) Sensors and devices to collect data and monitor the operation of the system.

C1 & C2 — Testing facility energy controls and monitoring systems

S3 — Climatic conditioning unit per paragraph 7.2.
S4 — Brake enclosure and sampling plane per paragraphs 7.4 & 7.5
S5 — Emissions measurement system per paragraphs 9.1 & 9.2
7. Test System Requirements

7.6. Sampling plane
Duct between outlet of the brake enclosure and the inlet of the sampling probes:
- Round with no changes in cross-section
- Inner diameter 175...225 mm
- Maximum one 90° bend with radius ≥ 2d
- Stainless steel + electropolish
- Minimal accumulation of debris ≤ 10 µm
- Sampling plane ≥ 6d downstream & ≥ 2d downstream

7.5. Sampling tunnel
- Sampling plane
- Sampling tunnel
- Duct between outlet of the brake enclosure and the inlet of the sampling probes
- Round with no changes in cross-section
- Inner diameter 175...225 mm
- Maximum one 90° bend with radius ≥ 2d
- Stainless steel + electropolish
- Minimal accumulation of debris ≤ 10 µm
- Sampling plane ≥ 6d downstream & ≥ 2d downstream

7.3. Brake dynamometer
The brake dynamometer is a technical system that provides the controlled kinetic energy to the brake under test. It primarily transforms rotational kinetic energy into thermal energy.

8.4.1 Brake assembly
- Axis of rotation concentric with enclosure axes
- Use only LO-U or LO-P fixture
- Low residual torque and vibration
- Mounting to: tailstock, caliper or backing plate, disc or drum; connect to dynamometer shaft

7.4. Brake enclosure
- Symmetrical on both axes
- Smooth transitions and surfaces
- L (1200...1400) mm
- H (600...750) mm
- D (400...500) mm
- Cone/trapezoid angle (15°...30°)
- 2-min, 9-point inlet speed variation within ± 35% (225 mm from axis)
- 2d entry round duct; stainless steel + electropolish
- Re > 4000 at entry

7.2. Cooling airflow
- Average section and max 1 Hz ± 5% Qset; ± 10% Qset for ≤ 5% section time
- 2-min leak check ± 5% Qset

7.2.3. Cooling airflow
- ≥ 5d downstream & ≥ 2d downstream
- Average section and max 1 Hz ± 5% Qset:
  ± 10% Qset for ≤ 5% section time
- Report actual and normalised conditions
- 2-min leak check ± 5% Qset
- Sensors accuracy (details in paragraph 14):
  ± 2% airflow; ± 1°C; ± 0.4 kPa

7.2. Climatic conditioning unit
- Qmin = (100...300) m³/h
- Qmax ≥ (Qmin + 1000 & ≥ 5-Qmin) m³/h
- (23 ± 2) °C
- (50 ± 5) % RH
- (6...11) gH₂O/kg dry air

7.2.2. Cooling air cleaning
- ≥ 99.95% or ≥ H13
- PNC zero verification ≤ 0.2 #/cm³
- Tunnel background ≤ 20 #/cm³
- Applies to 5-min average for TPN & SPN

7.2.1. Cooling air conditioning
- Parameter
  - Air temperature
  - Air Humidity
- Nominal
  - 23 °C
  - 50 %RH
- Average
  - ± 2 °C
  - ± 5 %RH
- 1 Hz
  - ± 5 °C
  - ± 30 %RH
- Maximum
  - –
  - –
- Exceedance per section
  - ≤ 10%
  - ≤ 10%

7.1. PM mass
Quantification of the particulate matter mass generated by the brake during the test
- Provide the emissions factors for the brake under testing in mg/km
- The test system shall measure brake PM10 and PM2.5 emissions gravimetrically using separate sampling systems for each cut-off diameter (2.5 µm and 10 µm)

12.1. PN concentration
Sampling and measurement to quantify the number of particles generated by the brake during the test
- Provide the emissions factors for the brake under testing in #/km
- Capable of measuring Total-PN (TPN10) and Solid-PN (SPN10) at a nominal particle size of approximately 10 nm electrical mobility diameter and larger

12.2. PN concentration
- Parameter
  - Air temperature
  - Air Humidity
- Nominal
  - 23 ± 2 °C
  - 50 ± 5 %RH
- Average
  - ± 2 °C
  - ± 5 %RH
- 1 Hz
  - ± 5 °C
  - ± 30 %RH
- Maximum
  - –
  - –
- Exceedance per section
  - ≤ 10%
  - ≤ 10%

7.2.1. Cooling air conditioning
- Parameter
  - Air temperature
  - Air Humidity
- Nominal
  - 23 °C
  - 50 %RH
- Average
  - ± 2 °C
  - ± 5 %RH
- 1 Hz
  - ± 5 °C
  - ± 30 %RH
- Maximum
  - –
  - –
- Exceedance per section
  - ≤ 10%
  - ≤ 10%

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- Parameter
  - Air temperature
  - Air Humidity
- Nominal
  - 23 °C
  - 50 %RH
- Average
  - ± 2 °C
  - ± 5 %RH
- 1 Hz
  - ± 5 °C
  - ± 30 %RH
- Maximum
  - –
  - –
- Exceedance per section
  - ≤ 10%
  - ≤ 10%

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- ± 10% Qset for ≤ 5% section time
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- ≥ 99.95% or ≥ H13
- PNC zero verification ≤ 0.2 #/cm³
- Tunnel background ≤ 20 #/cm³
- Applies to 5-min average for TPN & SPN

7.2.1. Cooling air conditioning
- Parameter
  - Air temperature
  - Air Humidity
- Nominal
  - 23 °C
  - 50 %RH
- Average
  - ± 2 °C
  - ± 5 %RH
- 1 Hz
  - ± 5 °C
  - ± 30 %RH
- Maximum
  - –
  - –
- Exceedance per section
  - ≤ 10%
  - ≤ 10%
8. Test Preparation Requirements

8.1. Vehicle and Brake Dynamometer Settings

Table 8.1 and 8.2 indicate all the required brake parameters that shall be available to the test facility.

\[ I_{t} = 0.87 \times I_{n} \text{ (Eq. 8.3)} \]

Brake Test Inertia – 13% reduction to account for vehicle road load losses

\[ M_{veh} = MRO + 37.5 \text{ kg} \]
\[ M_{veh} = MRO + 25 \text{ kg} + 0.28 \times MVL \]

8.2. Test Setup Preparation

Verification key steps- before starting the test.

- BRO \( \leq 50 \mu m \), 10 mm outwards of centerline or drum center
- Emission equipment shows no faults and PM filters are ready per manufacturer specs
- Perform a few static applies at 3...30 bar to verify brake fluid displacement and brake bleed
- Run ECU until setpoint values are stable
- Record drag to be \( \leq 20 \text{ N·m} \) at (5, 50 and 135) km/h for 10 seconds each. Accelerate at 1 m/s\(^2\) to 5 km/h and 2 m/s\(^2\) to 50 km/h and 150 km/h
- Brake apply # 1 of trip 1 repeated 10 times to verify data collection and overall system operation
- Verify background emission level are within limits per paragraph 7.2.2.2.2 at nominal airflow

8.3. Brake Temperature Measurement

Use embedded thermocouples as control

8.4. Brake Positioning

8.4.1. Brake assembly

Caliper at 12-O’clock position

Planes A1 and D are perpendicularly intersecting the axis of rotation

Figure 8.6 reflects mandatory disc rotation according to evacuation direction when driving forward

Figures 8.4 and 8.5 reflect the allowed fixture styles

#### 9.1. General Information
- One WLTP-Brake cycle: 10 individual trips
- Active speed control: 15,826 seconds
- Brake deceleration events: 303
- Distance: 192 km
- Average speed: 43.7 km/h
- Maximum speed: 132.5 km/h
- Average deceleration: 0.97 m/s²
- Maximum deceleration: 2.18 m/s²
- Average brake duration: 5.7 s
- Maximum duration: 15 s.

<table>
<thead>
<tr>
<th>9.2.1. Cooling adjustment section</th>
<th>9.2.2. Bedding section</th>
<th>9.2.3. Emissions measurement section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setup the brake per 8</td>
<td>Setup the brake per 8</td>
<td>Setup the brake per 8</td>
</tr>
<tr>
<td>Set airflow to a known value or 50% max setting</td>
<td>Set airflow per setting from brake cooling adjustment section</td>
<td>Verify nozzles, filters, airflow, and instrumentation per 12</td>
</tr>
<tr>
<td>Warm-up the brake to IBT = (40 ± 1) °C using decel. events #190…196</td>
<td>Commence 1st WLTP at IBT = (23 ± 5) °C</td>
<td>Commence Trip #1 at IBT = (23 ± 5) °C</td>
</tr>
<tr>
<td>Cool down to (40 ± 1) °C</td>
<td>Do not soak between trips</td>
<td>For Trips #2…10 wait for 30 °C ≤ IBT ≤ 40 °C</td>
</tr>
<tr>
<td>Conduct one Trip 10 without interruptions</td>
<td>Cool down to (40 ± 1) °C</td>
<td>Interruptions? Apply 9.3.3.</td>
</tr>
<tr>
<td></td>
<td>Test failure</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Repair, replace, and repeat</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Proceed to bedding section</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Setup iterations in report</td>
<td></td>
</tr>
<tr>
<td></td>
<td>no</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Report iterations in report</td>
<td></td>
</tr>
<tr>
<td></td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>Set new airflow</td>
<td>Issues per 9.3.1.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Diagram Notes:**
- **Dyno fault:** Indicates a malfunction requiring immediate attention.
- **Test failure:** Requires investigation and possible corrective action.
- **IBT < 30 °C?**
  - **Discontinue and fix**
  - **Repeat WLTP to complete five**
  - **Proceed to emissions measurement section**
- **30 °C < IBT < 40 °C?**
  - **Continue**
- **any Trip #2…10 at IBT < 30 °C?**
  - **Discontinue, fix, or repeat cooling airflow adjustment**
  - **Test output per 13**

**Equipment Testing Support:**
- **www.linkeng.com**
- 41100 Plymouth Rd., Suite 300
- Plymouth, MI 48170, U.S.
- Updated 21 March 2023

(9) Visit [https://unece.org/sites/default/files/2023-01/GRPE-87-40e_clean.pdf](https://unece.org/sites/default/files/2023-01/GRPE-87-40e_clean.pdf) for complete proposal.
9.4.1. Speed Violations
Upper limit: nominal speed within ± 1 s of a given point + 2 km/h
Lower limit: nominal speed within ± 1 s of a given point - 2 km/h
≤ 158 points = 3% for Trip #10 (cooling adjustment section)
≤ 475 points = 3% for Trip #1…10 (bedding or emissions measurement sections)

9.4.2. Number of Deceleration Events
The parameters “Stop Duration” and “Deceleration Rate - Distance Averaged” shall be cross-checked and verified that both include 303 numerical and non-zero values that correspond to the respective 303 brake events of the WLTP-Brake cycle. This quality check applies only to the emissions measurement section.

9.4.3. Kinetic Energy Dissipation
Sum of all specific friction work during brake deceleration events per trip and per cycle. Applies only to full-friction brakes.

\[ W_f = (2 \times \pi/60) \times f \times t_{\text{brake}} \times t_{\text{brake/WL}} \quad (\text{Eq. 9.1}) \]

\[ W_{M/S} = 0.5 \times 1822 \text{ kg} \times 0.77 \times 0.87 = 610.4 \text{ kg} \]

\[ \therefore W_f = (2 \times \pi/60) \times 750.0 \times 304.3 \times 9.3/610.4 = 383.7 \text{ N \cdot m} \]

10.1.1. Definition of Brake Groups for Cooling

Definitions:

\[ W_{L_n-f} = \text{Nominal Front Wheel load} \]
\[ D_M = \text{disc or drum mass} \]

1. First the WL/DM ratio to define brake group

- Group 1: \( W_{L_n-f}/D_M \leq 45; \)
- Group 2: \( 45 < W_{L_n-f}/D_M \leq 65; \)
- Group 3: \( 65 < W_{L_n-f}/D_M \leq 85; \)
- Group 4: \( W_{L_n-f}/D_M > 85. \)

2. Apply the required temperatures to brake events #46, 101, 102, 103, 104 and 106 of WLTP Trip 10

10.1.3. Brake Temperature Measurement

Target a cooling airflow that meets the three criteria (ABT, IBT, and FBT)

<table>
<thead>
<tr>
<th>Oset</th>
<th>ABT</th>
<th>IBT</th>
<th>FBT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>Max</td>
<td>OK</td>
<td>&gt;</td>
<td>&gt;</td>
</tr>
<tr>
<td>Min</td>
<td>&lt;</td>
<td>&lt;</td>
<td>&lt;</td>
</tr>
</tbody>
</table>

Note: Paragraphs 10.1.2.b and 10.1.2.c dictate the nominal cooling airflow defined for the front brake applies for rear (disc or drum).

11.1. and 11.2. Front Brakes and Rear Brakes

Setup the brake per 8
Set airflow per setting from brake cooling adjustment section
Commence 1st WLTP at IBT = (23 ± 5) °C
Do not soak between trips
Cool down to (40 ± 1) °C

30 °C < IBT < 40 °C? continue
IBT < 30 °C? discontinue and fix
Interruptions? Apply 9.3.2.
Repeat WLTP to complete five
Proceed to emissions measurement section

(12) Visit https://unece.org/sites/default/files/2023-01/GRPE-87-40e_clean.pdf for complete proposal
**12.1. Measurement PM Mass**  

**12.1.1. PM Sampling Nozzles**  
Stainless steel with electropolish finish  
Isokinetic ratio $0.9 \leq IR \leq 1.15$  
Minimum ID $\geq 4$ mm  
Constant diameter for $\geq 1$xID and $\geq 10$ mm  
(Outer diam./inner diam.) $\leq 1.1$ at nozzle tip  
Cross-section change $\leq 30^\circ$  
Nozzle axis to dilution tunnel $\leq 15^\circ$  
Clean before every test per nozzle spec.

**12.1.1.1. Sampling Plane**  
Detailed design per 7.6.  
Allocate one probe for PM$_{2.5}$ and one for PM$_{10}$  
For three-probe sampling, locate the PM probes at the bottom per Fig. 7.7. (left-side)  
For four-probe sampling, locate the PM probes at the bottom per Fig. 7.7. (right-side)  
Do not use flow-splitters for PM measurement anywhere in the sampling or measurement system

**12.1.1.2. Sampling Probes**  
Design to minimize particle losses  
Electroconductive material, electrically grounded, electropolished finish  
Constant inner diam. ($10$ mm $\leq d_p \leq 18$ mm)  
Length from nozzle tip to inlet of PM separation device $\leq 1$ m  
Maximum one 90° bend (bend radius $\geq 4d_p$)  
Clean nozzles per manufacturer spec or at least every two months of active use

**12.1.1.3. PM Sampling Nozzles**  
Stainless steel with electropolish finish  
Isokinetic ratio $0.9 \leq IR \leq 1.15$  
Minimum ID $\geq 4$ mm  
Constant diameter for $\geq 1$xID and $\geq 10$ mm  
(Outer diam./inner diam.) $\leq 1.1$ at nozzle tip  
Cross-section change $\leq 30^\circ$  
Nozzle axis to dilution tunnel $\leq 15^\circ$  
Clean before every test per nozzle spec.

**12.1.2. PM Sampling Flow**  
Flow measurement error: smallest between $\pm 2.5\%$ of reading or $\pm 1.5\%$ full scale  
Sensors to report standard flow: $\pm 1.0$ °C for temperature and $\pm 1.0$ kPa for pressure  
Average airflow flow shall remain constant during brake emissions measurement section within $\pm 2\%$ set (nominal)  
Set isokinetic ratio as close as possible to 1.0 (avg. during emissions section 0.9…1.15)  
Keep flow for $\geq 10$ s after emissions section

**12.1.2.1. PM Separation Device**  
Mounted at end of sampling probe  
Leak check: seal nozzle $\rightarrow$ start pump $\rightarrow$ measure flow to be $\leq 2\%$ normal flow at maximum vacuum  
Leak checks at installation, maintenance, or upgrades of the system  
PM sampling device shall operate continuously during brake emission measurement section (including soaking), no pause or bypass  
Keep flow for $\geq 10$ s after emissions section

**12.1.2.2. PM Sampling Line**  
Minimize transport losses  
Stainless steel or antistatic PTFE  
Constant inner diam. ($10$ mm $\leq d_p \leq 20$ mm), $15$ mm recommended  
Overall length from outlet of PM separation device to tip of filter holder $\leq 1$ m  
Avoid condensation and maintain temperature inside sampling train $\geq 15^\circ$C  
bend radius $\geq 25d_p$

**12.1.3. PM Sampling Line**  
Minimize transport losses  
Stainless steel or antistatic PTFE  
Constant inner diam. ($10$ mm $\leq d_p \leq 20$ mm), $15$ mm recommended  
Overall length from outlet of PM separation device to tip of filter holder $\leq 1$ m  
Avoid condensation and maintain temperature inside sampling train $\geq 15^\circ$C  
bend radius $\geq 25d_p$

**12.1.2.3. PM Sampling Flow**  
Flow measurement error: smallest between $\pm 2.5\%$ of reading or $\pm 1.5\%$ full scale  
Sensors to report standard flow: $\pm 1.0$ °C for temperature and $\pm 1.0$ kPa for pressure  
Average airflow flow shall remain constant during brake emissions measurement section within $\pm 2\%$ set (nominal)  
Set isokinetic ratio as close as possible to 1.0 (avg. during emissions section 0.9…1.15)  
Keep flow for $\geq 10$ s after emissions section

**12.1.2.4. isokinetic Ratio (IR)**  
$$IR = 0.06 \times \frac{(NQ_S/d_p^2)}{(NQ/d_i^2)} \quad (Eq. 12.4)$$  
$NQ_S$ is the avg. normalized airflow in the sampling nozzle in Nl/min  
$NQ$ is the average normalized airflow in the tunnel inNm³/h  
d$_p$ is the inner diam. at the nozzle tip in mm  
d$_i$ is the sampling tunnel’s inner diam. in mm

**12.1.3. Filter Holder**  
Use single 47-mm filter per test  
Locate it as close as possible to outlet of cyclonic separator  
Inert and non-corroding material (stainless steel or anodized aluminum)  
Use circular filters (exposed area 34…44 mm)  
Even flow distribution across stain area  
Avoid condensation and maintain temperature during test $\geq 15^\circ$C

**12.1.3.1. Filter Media**  
Fluorocarbon-coated glass fibre / fluorocarbon membrane  
0.3 µm collection efficiency $\geq 99\%$ at a gas filter face velocity of 5.33 cm/s per MIL-STD-282 methods (102.8 or 502.1.1), or IEST-RP-CC021  
Use only filter media certified by the supplier

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(13) Visit [https://unece.org/sites/default/files/2023-01/GRPE-87-40e_clean.pdf](https://unece.org/sites/default/files/2023-01/GRPE-87-40e_clean.pdf) for complete proposal

(a) Weighing room – free of ambient contaminants ● (22 ± 2) °C & (45 ± 8) %RH ● air flow for air exchange does not influence balance stability
(b) Weighing balance – use microbalance ● insolate from vibration, electrostatic forces, and air streams ● resolution ≤ 1 µg ● use calibration weights
(c) Static electricity effects – nullify by grounding with antistatic mat ● neutralize filter with polonium neutralizer or similar ● or, equalize static change

---

Retrieve two unused filters

Weighing room

Pre-sampling conditioning (d) ≥ 2 hours
Closed Petri-dish (or equivalent)

Filter weighing (g)

Transfer to filter holder in ≤ 1 h (d)
Closed Petri dish Filter holder

Perform brake emissions test

Transfer to weighing room in ≤ 8 h (e)
Closed Petri dish Filter holder

Weighing room

Post-sampling conditioning (e) ≥ 2 hours
Closed Petri-dish (or equivalent)

Filter weighing per (g)

Filter storage (e)
Closed Petri dish Filter holder

(f) – Reference filter weighing

Weighing room:

Pre-sampling conditioning (d) ≥ 2 hours
Closed Petri-dish (or equivalent)

Pre- Pe1(corr.) Pre- Pe2(corr.)

Pre-session weighing (g)

Perform weighing session including pre- and post-sampling

Post-session weighing (g)

Post- Pe1(corr.) Post- Pe2(corr.)

(Pre-Pe1(corr.) - Post-Pe1(corr.)) ± 10 µg

Moving average for 1...15 days ± 10 µg (f)

(14) Visit https://unece.org/sites/default/files/2023-01/GRPE-87-40e_clean.pdf for complete proposal
12.1.4. (g) Sample Filter Weighing

Retrieve pre- or post-sampling filter

Weighing room

Pre-sampling conditioning (d) ≥ 2 hours
Closed Petri-dish (or equivalent)

Weigh the filter twice (i)

\[ X_1 \quad X_2 \]

\[ \text{abs}(X_1 - X_2) \leq 30 \mu g \]

no

yes

Report the average (ii)

\[ p_{\text{uncorr.}} = \frac{X_1 + X_2}{2} \]

Take two more weighs (iii)

\[ X_3 \quad X_4 \]

\[ \text{Report the average (iv)} \]

\[ p_{\text{uncorr.}} = \frac{X_1 + X_2 + X_3 + X_4}{4} \]

\( r = X_{\text{max}} - X_{\text{min}} \)

reported by

\[ 38 \mu g < r \leq 42 \mu g \]

\[ (2) \]: second-lowest; \( (3) \): third-lowest

Reject weighing session (vi…viii)

Void filter and replace for pre-sampling, or repeat the brake emissions test for a post-sampling weighing session

Quarantine ≥ 24 h and repeat (i) and (ii). If range ≥ 30 µg, void filter and replace for pre- or post-sampling

Compute buoyancy correction (h)

Compute filter load and report per Table 13.6 & par. 13.4

(h) Filter Buoyancy Correction (all filters)

Air temperature in K

\[ 8.3144 \text{ J mol}^{-1} \text{ K}^{-1} \]

Atmospheric pressure in kPa

\[ 28.836 \text{ g mol}^{-1} \]

\[ p_a = \frac{(p_b \times M_{\text{mix}})}{(R \times T_a)} \]

\[ p_{\text{e(Corrected)}} = p_{\text{e(Uncorrected)}} \times \left[ 1 - \frac{(p_a/p_w)}{1 - (p_a/p_f)} \right] \]

From weighing session in mg

8000 kg/m³ for stainless steel or the known value for different materials. Follow OIML R 111-1 Edition 2004(E) (or equivalent)

(a) Fluorocarbon coated glass fibre filter:

2300 kg/m³

(b) Fluorocarbon membrane filter:

2144 kg/m³.

12.2.1.3. PN Sampling Nozzles
Stainless steel with electropolish finish
Isokinetic ratio $0.6 \leq IR \leq 1.5$
Minimum ID $\geq 4 \text{ mm}$
Constant diameter for $\geq 1 \times \text{ID}$ and $\geq 10 \text{ mm}$
(Outer diam./inner diam.) $\leq 1.1$ at nozzle tip
Cross-section change $\leq 30^\circ$
Nozzle axis to dilution tunnel $\leq 15^\circ$
Clean before every test per nozzle spec.

12.2.1.2. Sampling Probes
Design to minimize particle losses
Electroconductive material, electrically grounded, electropolished finish
Constant inner diam. ($10 \text{ mm} \leq d_p \leq 18 \text{ mm}$)
Length from nozzle tip to inlet of PN pre-classifier $\leq 1 \text{ m}$ and $\leq 3 \text{ residence time}$
Maximum one $90^\circ$ bend ($\geq 4d_p$)
Clean nozzles per manufacturer spec or at least every two months

12.2.2.1. PM Separation Device
One for each probe (TPN10 and SPN10)
One upstream of flow-splitter
One for each downstream of flow-splitter
Use commercial units: $2.5 \mu \text{m} \leq d_{50} \leq 10 \mu \text{m}$
Inspect and clean inner walls per manufacturer specifications

12.2.2.2. Sample Conditioning
$\geq 1$ particle diluter (no heating for TPN10)
Electrically conductive material, grounded, and with minimal particle deposition
$\geq 1$ stage with $\geq 10:1$ dilution ratio to remain $\leq$ upper limit of single-particle count mode
Dilution factor $\pm 5\%$ of set value, diluted gas $\leq 38 ^\circ \text{C}$, with $\geq$ H13 filter (or equivalent)
Monitor and report average PCRF at 1 Hz
Report PCRF-corrected TPN10 and SPN10 at std. conditions $\geq 0.5 \text{ Hz}$
Penetration efficiency $\geq 70\%$ at 100 nm
Sample pressure $850 \ldots 1050 \text{ mBar}$ at $\pm 50 \text{ mBar}$ from ambient pressure

12.2.3.1. Particle Number Counter (PNC)
Operate under full flow conditions;
Readability $\geq 0.1 \# / \text{cm}^3$ at $\leq 100 \# / \text{cm}^3$
Counting accuracy $\pm 10\%$; $1 \# / \text{cm}^3 \rightarrow$ upper threshold for single-particle count
Linear response and $t_{90} \leq 5s$
Traceable internal cal. factor; calibrate with emery oil, soot-like, silver particles; $(65 \pm 15\%)$ at 10 nm and $\geq 90\%$ at 15 nm

12.2.3.2. PN Sampling Flow
Maximum permissible error $\pm 5\%$
Sensors to report standard flow: $\pm 1.0 ^\circ \text{C}$ for temperature and $\pm 1.0 \text{ kPa}$ for pressure
Normalized airflow $\pm 10\%$ of 1 Hz average
PM sampling device shall operate continuously during brake emission measurement section (including soaking and post-test background), no pause or bypass

12.2.3.3. PN Internal Transfer Line
Minimize particle losses DIL1/VPR $\rightarrow$ PNC
Electrically conductive material not reactive
Constant inner diameter $\geq 4 \text{ mm}$ and laminar flow under all operating conditions
Overall length from DIL1/VPR $\rightarrow$ PNC $\leq 1 \text{ m}$
Particle residence time $\leq 1 \text{ s}$
bend radius $\geq 10_{p}$
12.3. Mass Loss Measurement

Weighing room – free of ambient contaminants

- (22 ± 2) °C & (45 ± 8) %RH
- provide information on robustness and correctness of the overall test
- weighing scale resolution ≤ 0.1 g for parts ≤ 20 kg
- verify stability and proper function with calibration weights every month
- measure initial and final mass of brake assembly before and after testing
- do not disrupt brake assembly during brake emissions test

Retrieving brake parts (friction material, disc/drum)

- Vacuum clean all parts
- Inspect all parts (burs, cracks, voids, or detachment)

Weighing room

(Initial) Weight each part with thermocouple installed:

- Friction material with anti-noise shims, springs, other h/w part of the assembly
- Disc / drum
  - Remove thermocouple connector

Perform brake emissions test

Room with controlled temperature and humidity

- Cooldown parts to ≤ 30 °C storing ≥ 24 h
- Clean parts to remove grease or contamination

Mass measurement file

Mass loss for each part = initial - final

Overall mass loss for each part = \( \sum \) (mass loss for each part)

Averaged weight loss emissions factor = overall mass loss / total distance

Weighing room

(Final) Weight each part with thermocouple installed:

- Friction material with anti-noise shims, springs, other h/w part of the assembly
- Disc / drum
  - Remove thermocouple connector

Test complete

- Disassemble and dispose of test parts
- Mass measurement file

Staggering of Initial and Final mass measurements with test sections

- new parts
  - cooling
  - bedding
  - emissions
  - F

- prior parts
  - cooling
  - new parts
  - bedding
  - emissions
  - F

(17) Visit https://unece.org/sites/default/files/2023-01/GRPE-87-40e_clean.pdf for complete proposal

Four Main Outputs of a Brake Emissions Test are Needed:

13.1. Event-Based File
- Raw Data
- Cooling
- Bedding 1-5
- Emissions

Table 13.1: Required parameters per tab and by column. 21 columns total, data at 250 Hz

13.2. Time-Based File
- Raw Data
- Pre-test Background
- Bedding 1-5
- Emissions

Table 13.2: Required parameters per tab and by column. 29 columns total, data at 10 Hz

13.3. Mass Measurement File
- PM Measurement data
- Reference Filter Data
- Brake Wear or Mass Loss

Table 13.3: Needed for brake tested 29 columns
Table 13.4: Needed 13 columns

13.4. Test Report File

Table 13.6: PDF report with complete dataset of specific brake tested 280 parameters and test input are included on this summary report

PM10
PM 2.5

(18) Visit https://unece.org/sites/default/files/2023-01/GRPE-87-40e_clean.pdf for complete proposal
### 14. Calibration and Ongoing QC

<table>
<thead>
<tr>
<th>System or Instrument</th>
<th>Paragraph</th>
<th>Initial Manufacturer Compliance</th>
<th>Months</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brake dynamometer (rotational speed, torque, pressure, fluid displacement, temperature)</td>
<td>14.2.</td>
<td><img src="https://www.linkeng.com/images/mandatory.png" alt="●" /></td>
<td>0 ... 6 ... 12 13</td>
</tr>
<tr>
<td>Cooling airflow measuring device</td>
<td>14.3.</td>
<td><img src="https://www.linkeng.com/images/depending.png" alt="●" /></td>
<td><img src="https://www.linkeng.com/images/recommended.png" alt="●" /></td>
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<tr>
<td>Cooling airflow temperature and atmospheric pressure</td>
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</tr>
<tr>
<td>PM&lt;sub&gt;10&lt;/sub&gt; and PM&lt;sub&gt;2.5&lt;/sub&gt; cyclonic separators</td>
<td>12.1.</td>
<td><img src="https://www.linkeng.com/images/mandatory.png" alt="●" /></td>
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</tr>
<tr>
<td>PM sampling flow measuring device</td>
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<td><img src="https://www.linkeng.com/images/depending.png" alt="●" /></td>
</tr>
<tr>
<td>PM sampling flow temperature and pressure sensors</td>
<td>12.1.</td>
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<td><img src="https://www.linkeng.com/images/depending.png" alt="●" /></td>
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<tr>
<td>Microgram balance (filters) and brake parts balance</td>
<td>14.4.</td>
<td><img src="https://www.linkeng.com/images/mandatory.png" alt="●" /></td>
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<td>PN cyclonic separator</td>
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<tr>
<td>PN sampling flow measuring device</td>
<td>12.2.</td>
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<tr>
<td>PN sampling flow temperature and pressure sensors</td>
<td>12.2.</td>
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<td><img src="https://www.linkeng.com/images/depending.png" alt="●" /></td>
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<tr>
<td>Dilution system for TPN10 and Volatile Particle Remover (VPR) for SPN10</td>
<td>14.5.</td>
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<td>Particle Number Counter (PNC)</td>
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<td>Microbalance for PM filters and balance for brake parts weighing</td>
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<td><img src="https://www.linkeng.com/images/depending.png" alt="●" /></td>
</tr>
</tbody>
</table>

**Legend:**
- ![●](https://www.linkeng.com/images/mandatory.png) mandatory
- ![●](https://www.linkeng.com/images/depending.png) depending on the setup
- ![●](https://www.linkeng.com/images/recommended.png) recommended by LINK (not stated explicitly in GRPE-87-40)

At any major setup maintenance

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**Linearity requirements for brake rotational speed, torque, and brake; airflow; filter and brake parts weighing balance. See Tables 14.4...14.6 for \(a_0\), \(a_1\), \(SEE\), and \(r^2\)**
Thank You!

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Established in 1935