Proposal for the Annex C of the new UN GTR on Laboratory Measurement of Brake Emissions for Light-Duty Vehicles

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1. Purpose

This document provides the procedure to determine vehicle-specific friction braking share coefficients for use with the Global Technical Regulation on the measurement of brake wear particulate matter and particle number emissions from brakes used on Light-Duty vehicles. The method described in this annex may be used as an alternative to the friction braking share coefficients of the GTR, given in paragraph 5.2 table 5.1.

2. Scope and application

The GTR on Brake Particle Emissions is applied to all types of light duty vehicles. The method described in this Annex C shall be applied to all vehicle types with non-friction braking capabilities. It is meant as enhancement for Table 5.1., and describes the alternative, vehicle specific method for establishing of the Friction Braking Share Coefficients for vehicle types NOVC-HEV Cat.1, NOVC-HEV Cat.2, OVC-HEV and PEV.

This annex C describes the method setup and procedures for running WLTP-Brake Cycle tests on a chassis dynanometer and how to determine the vehicle-specific friction braking coefficient. It states a procedure and acceptance criteria for the use of alternative methods. Furthermore, it provides a procedure how to transform the vehicle specific friction share measured of the vehicle running on the WLTP-Brake-Trip10, or the WLTC (Exhaust) to vehicle-specific friction braking share coefficient of the identical vehicle running on WLTP-Brake Cycle.

[3. Definitions

3.1. Vehicle and Brake Dynamometer settings

3.3.1. "*Wbrake*" means the sum of the energy dissipated at all brakes during all braking events.

3.3.2. "*Wtotal*" means ….

3.3.3. ….

3.2. Test system

3.2.1. "Torque measurement sensor" means a electromechanical device that converts the torsional strain on the brake assembly into the equivalent output. The equivalent torque derives from the angular deceleration rate and the effective brake inertia. Alternatively, a device can be used to measure the force at the brake calliper and calculate the according torque by use of the correct geometric parameters.

3.2.2. Pressure sensor" for this annex means an electromechanical device that is connected to the brake fluid path close to the brake system and provides a signal that is equivalent to the brake pressure at the corresponding brake corner.

3.2.3. "Pressure to Torque ratio" (Cp) is a constant that converts the brake pressure (Pa) into braking torque (Nm) of a friction brake.

3.2.4. "Dynamic rolling radius" is the radius of the tire mounted on at the vehicle wheel of the tested brake corresponding to the vehicle speed.

3.2.5. “Vehicle speed” is the vehicle speed as given by the drive curve of the chassis dynamometer

3.2.6. “Set vehicle speed” corresponds to the setpoint of the vehicle speed at a certain time of the test

3.2.7. ….

4. Abbreviations and Symbols

Symbol/Abbreviation	*Definition*	*Unit*	*Paragraph*
pbrake	Measured braking pressure	bar	
Tbrake	Measured braking torque	Nm	
v	Measured vehicle speed	m/s	
r	Dynamic rolling radius of tire	m	
Wbrake	Friction work, which is the sum of the energy dissipated at all brakes during all braking events	J	
Wtotal,bc	Sum of the kinetic energy of the vehicle during all braking events. For the WLTP-Brake Cycle Wtotal,bc is calculated by multiplying the vehicle test mass Mveh with 15983 J/kg	J	
Wref,bc	Sum of kinetic energy during all braking events (Wtotal,bc) of the WLTP brake cycle, reduced by road load contribution share of 13%. Wref = Wtotal x 0.87	J	
Wtotal,ec	Sum of the kinetic energy of the vehicle during all braking events. For the WLTC (Exhaust) Wtotal,ec is calculated by multiplying the vehicle test mass Mveh with 3578 J/kg		
Cp	Pressure to Torque ratio converting measured brake pressure (Pa) into braking torque (Nm)	Nm/Pa	
c	Friction braking share coefficient	-	

5. Method Overview and Calculation Method

The vehicle individual friction share coefficient shall be determined on a fully GTR15 compliant chassis dynamometer applying the WLTP Brake test cycle. All brakes shall be equipped with external sensors to determine the brake torque at each of the wheels.

5.1 Calculation Method of Friction Share c

In the main GTR the brake particle emission factors are determined on a brake dynamometer, which is set to the respective road load considering reducing the inertia by 13% of the vehicle mass. In order to be consistent, the friction share coefficient is calculated as ratio of “stopping energy dissipated by the friction brakes” divided by “total stopping energy less road loads (defined as 13% in the GTR)”.

<u>Friction braking share coefficient</u>

$$\mathbf{c} = \frac{W_{\mathbf{brake}}}{W_{\mathbf{ref}}} \qquad \textit{(Eq. 1)}$$

Where:

c is the friction braking share coefficient.

W_{brake} is the sum of energy dissipated at the full-friction brake during all braking events in J;

$W_{ref, bc}$ is sum of kinetic energy during all braking events (W_{total}) reduced by arbitrary road loads of 13%, $W_{ref} = W_{total} * 0.87$ in J.

$W_{total, bc}$ is the sum of the kinetic energy of the vehicle during all braking events, reduced by 13% to consider road load losses. In case of WLTP-Brake Cycle the W_{total} is calculated by multiplying the vehicle test mass M_{veh} by 15983 J/kg. In case of WLTP-Brake-Trip 10 the W_{total} is calculated by multiplying the vehicle test mass M_{veh} by 5555 J/kg. In case of WLTC (Exhaust) W_{total} is calculated by multiplying the vehicle test mass M_{veh} by 3578 J/kg.

The friction share coefficient is determined for the vehicle running on the WLTP-Brake Cycle. Alternatives and acceptance criteria are described in paragraph 8 of this annex.

5.2. Method to determine the friction work Wbrake

The energy dissipated at hydraulic full-friction brakes is calculated from the measured brake pressure (p_{brake}) multiplied by the pressure to torque ratio (Cp) at the respective front and rear brakes (representing front and rear axle) during the brake applications of the driving cycle.

[Note: In the following the formula are written not yet specified for front and rear brakes. This needs to be separated into front axle and rear axles].

$$W_{\text{brake}} = Cp \sum_{i=1}^{N} \int_{0}^{t_{i-th}} p_{\text{brake}} \cdot 10^5 \cdot \frac{v}{r} \, dt$$

(Eq. 2)

Where:

Wbrake events	is the sum of energy dissipated at the full-friction brake during all braking in J;
Cp	is the Pressure to Torque ratio in Nm/Pa;
p_{brake}	is the brake pressure measured in bar;
v	is the vehicle speed as given by the drive curve in m/s;
r	is the tire dynamic rolling radius in m;
t	is the duration of a braking event in s.

The energy dissipated at electromechanical full-friction brakes is calculated from the measured electric power (P_brake) multiplied by the electric power to torque ratio (Cx) at the respective front and rear brakes (representing front and rear axle) during the brake applications of the driving cycle.

[Note: the formula to calculate Wbrake for electromechanical brakes has to be added]

5.3 Determination of Cp and Cx value

The determination of the Cp value, or Cx value for a specific brake system is based on a test run applying the WLTP-Brake Cycle. The test must be run on a brake dynamometer fully complying to this GTR.

5.3.1 Calibration of Brake Dynamometer

Ensure validity of the calibration of sensors used during the brake dynamometer test. All testing equipment must be calibrated and maintained per ISO 17025, "General requirements for the competence of testing and calibration laboratories (ISO/IEC 17025:2017)"

5.3.2. Operation

1. Install the brake according to the measurement procedure of this GTR.
2. Run WLTP-Brake test according to this GTR
3. Depending on brake type, record:
   a. brake torque and brake pressure for hydraulic or electro-hydraulic brake, or
   b. brake torque and electric power (current, voltage and additional required signals) for a electromechanical brake.
   Note: Usage of "Slow sampling rate" channels for the Cp evaluation as per 3.1.29. is allowed.

5.3.3. Cp calculation

Cp value describes the relationship between brake pressure and brake torque:

$$Cp = \frac{Brake\,Torque}{Brake\ \Pr essure}$$

(Eq. 3)

For a given friction material, C_p may depend on vehicle speed, applied brake pressure, brake rotor and pad temperature. It may change from snub to snub during the execution of the test.
To reduce the influence of Cp variability on brake energy calculation in the test cycle, “energy weighted Cp value” according to the formula below is used:

$$\boldsymbol{Cp_{avg}} = \frac{\int_{t=0}^{End} \boldsymbol{if(a(t)<0\&p(t)>0{,}5bar)\,then\,v(t)\times a(t)\times\frac{Tq(t)}{p(t)}dt}}{\int_{t=0}^{End} \boldsymbol{if(a(t)<0\&p(t)>0{,}5bar)\,then\,v(t)\times a(t)\;dt}} \qquad \textit{(Eq. 4)}$$

Note: Following limitations apply:

- Negative deceleration (braking)
- Brake pressure > 50kPa (0.5 bar) to avoid numeric instabilities

In case of running WLTP-Brake-Trip 10 on the Chassis Dynamometer for establishing of the friction share (see paragraph 8.1.) the Cp or Cx evaluation as described above should be carried out for data of WLTP-Brake-Trip 10.

6. Testing Setup and Specifications

6.1. Vehicle preparation

6.1.1 Pressure transducers and sensors and its calibration

For this method, an external pressure sensor shall be mounted to the brake fluid path for each brake corner of the vehicle. Preferably, it shall be mounted to the venting screw of the respective brake corner. If this is not possible due to space limitations or other issues, alternative mounting locations are allowed, however they should be located as close as possible to the according brake corner. The measured pressure over time shall be converted to brake energies and to c-factors according to the equation 1 and 2 described in chapter 5.1. and 5.2.

A range of 0 – [20000 kPa] is recommended, while the maximum range of the sensor shall be chosen according to the existing maximum pressure conditions during the tests.

Sensor calibrations shall meet the following specifications:

- o uncertainty of measurement for pressure measurement- [0.5%] of reading or [0.1%] of full scale whichever is larger (entire uncertainty budget)

To avoid zero drift, the pressure sensors shall be adjusted to zero before the test with no brake pressure applied to the system.

After the test, the pressure sensors shall be checked for zero drift. A max. zero-drift of [+/- XXX Pa] is acceptable.

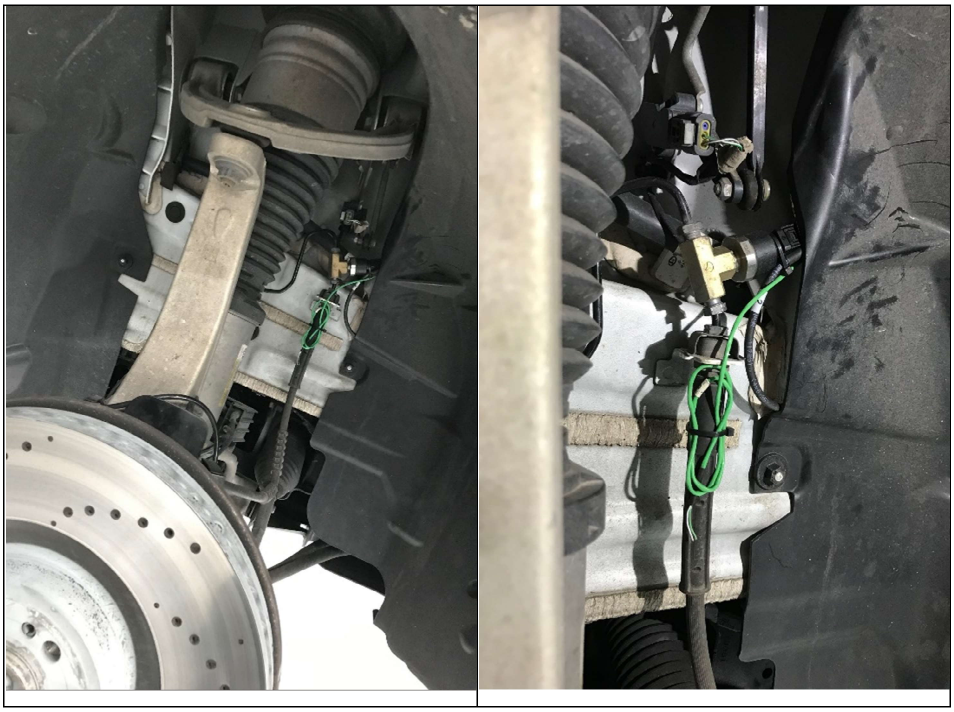

Figure 6.1. Brake pressure sensor at brake pipe to brake hose connection

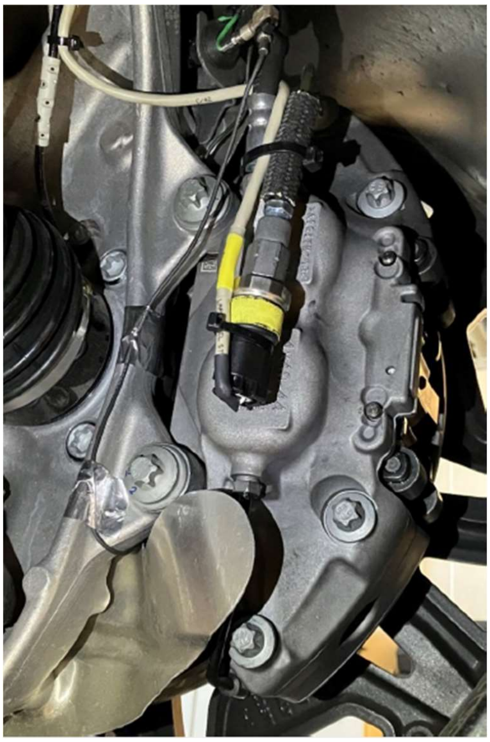

Figure 6.2. Brake pressure sensor at brake vent screw

6.1.2. Sensors for force measurements on electro-mechanical brake systems (EMB) and its calibration

If the brake systems of the vehicle operate without brake fluid, it is required to derive the braking energies from different sources. For EMB it is required to measure the electric current and voltage to calculate the brake power and convert it to brake energy according to equations … in chapter …

Measurement ranges of 0-…V and 0-…A are recommended, and the sensors shall meet the following specifications:

[more details to be added]

6.2. Data recording

6.2.1. Chassis Dynamometer Data

During testing, dedicated data recording systems have to be used to log the raw data from the chassis dynamometer as well as from the vehicle and its instrumented components.

The data recording recommendations are referred to GTR 15 (Annex B5, chapter 2 Chassis Dynamometer).

The dynamometer shall have a time measurement system for use in determining acceleration rates and for measuring vehicle/dynamometer coastdown times. This time measurement system shall not exceed an accuracy of ±0.001 per cent after at least 1,000 seconds of operation. This shall be verified upon initial installation.

The dynamometer shall have a speed measurement system with an accuracy of at least ±0.080 km/h. This shall be verified upon initial installation.

Roller speed shall be measured at a frequency of not less than 10 Hz.

For testing in 4WD operation, the speed difference between the front and rear rollers shall be assessed by applying a 1 second moving average filter to roller speed data acquired at a minimum frequency of 20 Hz.

Additionally to the data requested in GTR15, foundation brake related parameters have to be recorded. This includes at least the brake torque in Nm and the brake pressure in bar. The measurement has to be done with a frequency of not less than 10 Hz.

Regarding the vehicle masses, different specifications for the test mass have to be fulfilled:

- WLTC (Exhaust): MRO + 25kg luggage + 25kg opt. +15% Vehicle Mass
- WLTP-brake: MRO + ½ driver 37.5kg + 25 kg opt.

Moreover, the following input parameters must be documented:

- Dynamic rolling radius of tire
- Cp values

The data recording of dynanometer and vehicle has to ensure synchronized data, meaning that the signals have to refer to the same time trace.

Recorded data has to be provided in a common and open access data format.

6.3 Chassis Dynanometer Settings

The tests are setup and performed as described and specified in the currently valid version of UN GTR No. 15 as available at (https://wiki.unece.org/display/trans/Latest+GTR+15). For brake energy determination the 4-phase WLTC Class 3 cycle shall be used. No deviations, except the definitions in this document, are valid.

6.3.1. Consideration of Road Loads

For both test cycles, WLTC (Exhaust) and WLTP Brake Cycle, the road load simulation is considered to be fully compliant to GTR No. 15. This means, that the road load coefficients (f0, f1, f2) of the road load equation are taken into account for the test execution.

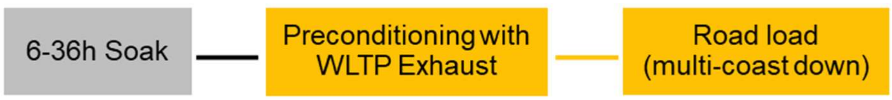

Figure 6.3. Principle Structure of road load adaptation according to this section

6.4. Test Sequence WLTP Brake

The test vehicle shall be run-in in accordance with the requirements in paragraphs 2 to 2.3. of Annex 8 to UN GTR No. 15

Generally the test is carried out by applying the sequence of preconditioning, soaking and (for OVC-HEV and PEV) recharging, followed by the performance test to derive the friction braking share (See Figure 6.4.). The requirements for those shall be as set out in Annex 8 of UN GTR No. 15, and particularly the following sections corresponding to the vehicle type being tested:

- NOVC-HEV (Cat.1 and Cat.2) – paragraphs 3.3.1.1.to 3.3.3.1.
- OVC-HEV – paragraphs 2.2. to 2.2.3.2. of Appendix 4 and paragraphs 3.2.4.2.1. and 3.2.4.2.2.
- PEV – paragraphs 3.4.2. to 3.4.4.1.

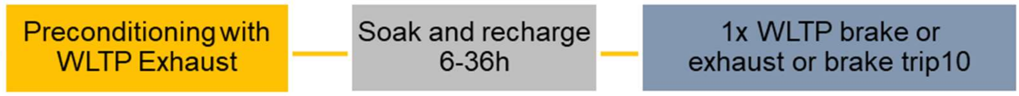

Figure 6.4. Principle Structure of chassis dyno testing according to this section

Notwithstanding the above requirements, the applicable test cycle during the performance test shall be the WLTP-Brake Cycle as described in Annex A. For OVC-HEV and PEV the cycle shall be driven only once regardless whether the break-off criteria has been reached or not.

In line with the provisions in paragraph 8 of this Annex the applicable test cycle above may be replaced by either:

- the WLTP Trip #10 of the WLTP-Brake cycle, or;
- the WLTC (Exhaust) cycle, being the 4-phase test cycle Class 3b as prescribed in paragraphs 3.3.2. to 3.3.2.5. of Annex 1 to UN GTR No. 15.

Speed trace tolerances shall be the ones described in (a) and (b) of paragraph 9.4.1. of this GTR. The number of speed violations shall not exceed a number corresponding to 3% of the applicable test cycle duration.

In case the vehicle cannot follow the speed trace of any of the cycles above, the friction brake share in Table 5.1. of this GTR shall be used by default.

7. Equivalence of Methods

At the option of the manufacturer and if the equivalence criterion described in paragraph 7.3 is fulfilled, an alternative method may be used for the determination of the individual friction share coefficient instead of the method described in paragraph 5.

7.1. Selection of Vehicle and Electrification Concept for Proof of Equivalence

The manufacturer shall demonstrate the equivalence of the alternative method to the reference method for each powertrain category (i.e. the familiy head for NOVC-HEV Cat.1, NOVC-HEV Cat2, OVC-HEV, and PEV).

7.2 Testing of the Alternative Method.

In order to prove equivalence, the vehicle shall be equipped with brake pressure transducers and sensors as indicated in paragraph 6.1 and shall be subjected to the WLTP-Brake Cycle according to the test sequence indicated in paragraph 6.4.

7.3. Equivalance Criterion

The alternative method shall be deemed to be equivalent to the reference method if the following condition is fulfilled:

$$\frac{W_{brake,alt}}{W_{brake,ref}} > 1.[x] \qquad (Eq. 5)$$

Where:

$W_{brake,alt}$ is the friction work calculated through the alternative method

$W_{brake,ref}$ is the friction work calculated according to Eq. 2

8. Equivalence of Test Cycle

As an alternative to derive the friction braking share coefficient from WLTP-brake cycle, the manufacturer may choose to calculate it from WLTP-Brake-Trip-10 or from WLTC (Exhaust)

8.1. WLTP-Brake- Trip 10

8.1.1. Calculation of Friction share from WLTP-Brake-Trip-10

The friction braking share coefficient can be calculated from WLTP-Brake-Trip-10 as follows:

$$c = c_{trip10} \cdot k_{br,trip10} \qquad \textit{(Eq. 6)}$$

where:

c_{trip10} is the friction braking share coefficient calculated on WLTP-Brake-Trip-10 cycle according to Eq.1 where the friction work *Wbrake* is calculated either according to Eq. 2 or with an alternative method as described in paragraph 7.

$k_{br,trip10}$ is a [constant] correlation factor between WLTP-brake cycle and WLTP-Brake-Trip-10

8.2. WLTC (Exhaust)

8.2.1. Calculation of Friction Share from WLTC (Exhaust)

The friction braking share coefficient can be calculated from WLTC (Exhaust) as follows:

$$c = c_{exhau} \cdot k_{br,ex} \qquad \textit{(Eq. 7)}$$

where:

$c_{exhaust}$ is the friction braking share coefficient calculated on WLTC (Exhaust) according to Eq.1 where the friction work *Wbrake* is calculated either according to Eq. 2 or with an alternative method as described in paragraph 7.

$k_{br,ex}$ is a [constant] correlation factor between WLTP-brake cycle and WLTC (Exhaust).

If $c_{exhaust}$ is lower than [x%], Eq. 6 shall not be used and the friction braking share coefficient shall be calculated either from WLTP-Brake cycle or from WLTP-Brake-Trip-10 according to paragraph 8.1.2 .

8.3. Offset of the friction braking share coefficient ("declaration")

The friction braking share coefficient calculated according to paragraphs 8.1. and 8.2. may be increased by the manufacturer to cover the statistical uncertainties related to the use of the correlation factors in Eq. 6 or in Eq. 7,

9. Test Output

….]