European Commission

PARTICLE MEASUREMENT PROGRAMME

PMP-IWG Meeting – 23 November 2022

“Non-Friction Braking”
JRC’s Proposal and TF4 updates

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INTRODUCTION - TF4 INITIAL OBJECTIVES

- ✓ TF4 shall propose a ***simplified methodology*** for introducing particle emissions testing of brakes that are mounted on electrified vehicles with regenerative braking capability in the overall PMP methodology;

- ✓ The proposal must be ***open and transparent***. The proposal shall take into account – to the extent possible – the replication of the vehicle's regenerative braking strategy;

- ✓ The proposal shall be ***reproducible and accessible to "third party" testing***, at minimum by introducing generic parameters that could be considered as representative of the actual vehicle capabilities;

- ✓ The proposal shall take into account – to the extent possible – the current state of the knowledge, expertise in the testing facilities, and brake dyno capabilities.

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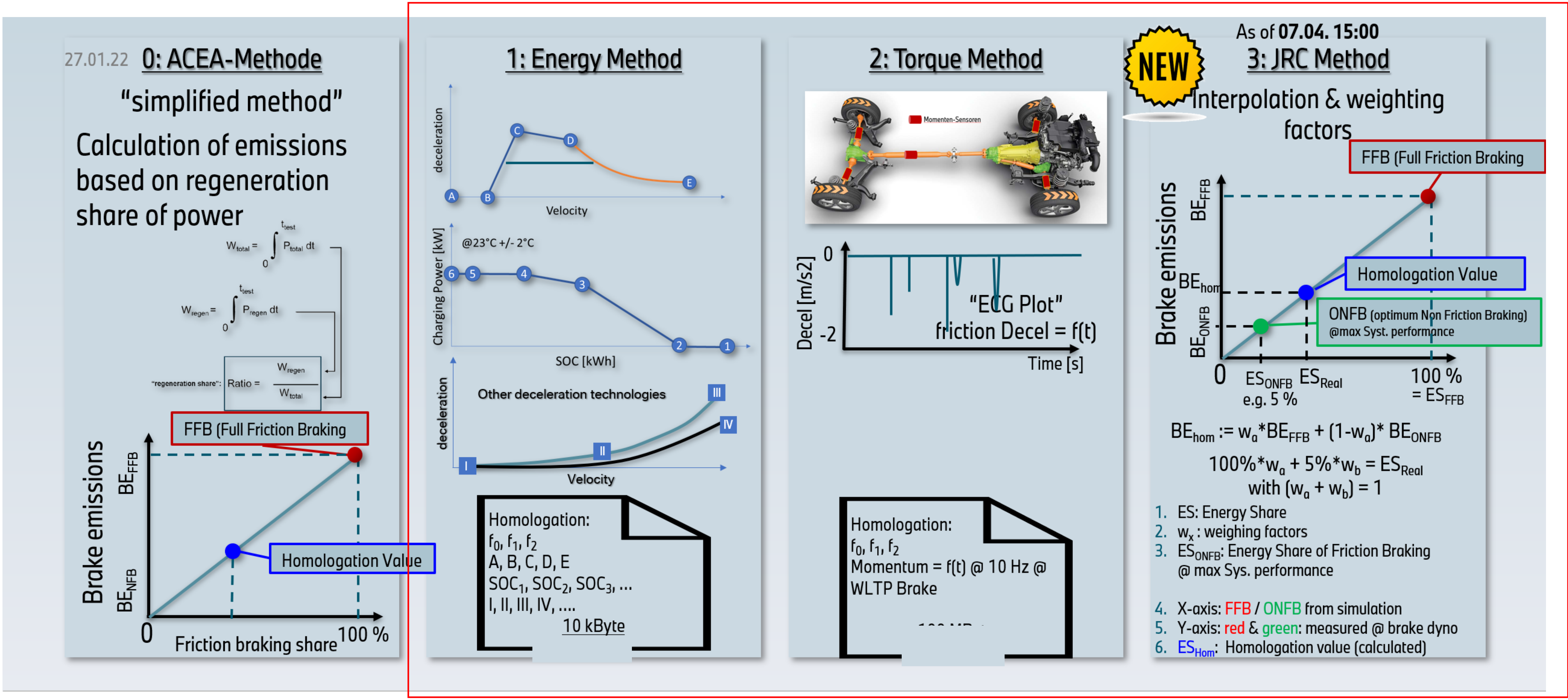
METHODS UNDER DISCUSSION BEFORE JUNE 2022



** Slide presented by OICA at the 19th TF4 Meeting on 28.04.2022 – Slide reflects the status when TF4 discussions were paused*

DIFFICULTIES & CONCERNS – OICA PROPOSAL

- ✓ OICA proposal uses time based brake torque signals provided by CAE models:

  a. There is no common model used for this purpose that could be validated as an open tool;

  b. The validation of individual CAE models would require a long and time-consuming procedure whereas it is not understood whether and how they could be considered for a regulatory approach;

- ✓ The proposal is not accessible to "third party" testing. The use of individual CAE models (if validated) would be proprietary information. This information is not available to the "outside world";

- ✓ Currently available brake dynos come with certain capabilities – It will require time until they reach the point where enhanced simulation of brake regeneration is achieved and more time before they become commercially available – The more complex the method the more time will be needed (applies also to JRC's proposal in next slide).

DIFFICULTIES & CONCERNS – JRC PROPOSAL

- ✓ Low energy testing might lead to higher testing uncertainty for the "best-case scenario" point. This is due to highest regenerative capability which will lead to very low use of friction brakes and thus very low emissions especially for BEV and PHEV;

- ✓ The application of generic polygons from third party testing facilities for all vehicle categories might create situations where the tested vehicle is not represented correctly. This could lead to cases where OEM and third party values are completely different;

- ✓ Adds one testing WLTP-Brake cycle (with cooling sections) in an anyway long testing procedure. Adds complexity to the overall method and requires additional testing capabilities from the testing facilities in terms of dyno or other equipment.

- ✓ The more complex the method the more time will be needed (applies also to OICA's proposal in previous slide).

JRC'S PROPOSAL – OVERVIEW

Need to define – in the very short term – a simplified method that would tackle the existing issues and provide the means for testing brakes mounted in vehicles with regenerative capabilities:

- ✓ The current proposal[1] applies the already defined concept for full-friction brakes and utilizes fixed coefficients for different vehicle categories based on their "electrification level" to calculate PM and PN emissions;
- ✓ A common fixed coefficient is proposed for each vehicle category. Different vehicles categories will have different fixed coefficients (4 coefficients to be defined: PEV, OVC-HEV, NOVC-HEV, Mild-Hybrid)[2]

FINAL BRAKE EMISSION FACTOR = FULL-FRICTION EMISSION FACTOR * FIXED COEFFICIENT

[1] The proposed method uses elements from the proposal submitted by ACEA at the TF4 on 02.12.2021

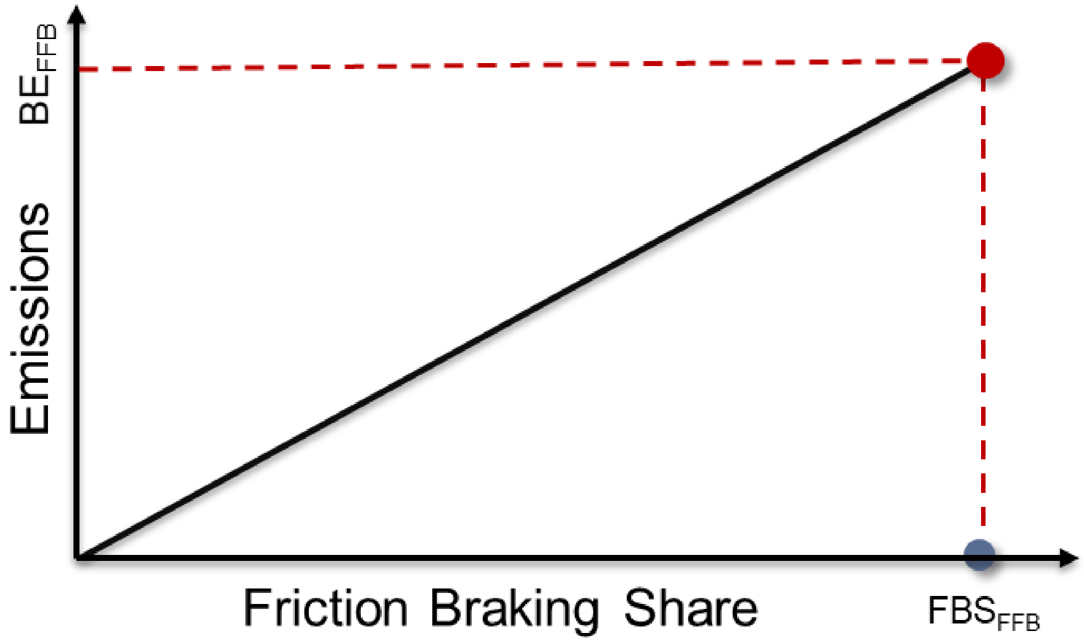
[2] The NOVC-HEV category will have to split into two sub-categories for "mild" and "regular" hybrids

JRC'S PROPOSAL – TESTING

Full-friction behavior: The brake is ALWAYS tested for its particle emissions assuming that the vehicle on which is mounted on has no non-friction braking capabilities (Full-Friction Brake = FFB).

- ✓ The protocol developed for full-friction brakes is applied for measuring particle emissions of the brake under testing;
- ✓ The test inertia and vehicle characteristics of the actual vehicle where the brake is mounted on is assumed (i.e. PEV). The test inertia is reduced by 13% to account for parasitic losses;
- ✓ The PM and PN emission factors of the FFB scenario are calculated based on the methods described in the submitted formal GTR document.

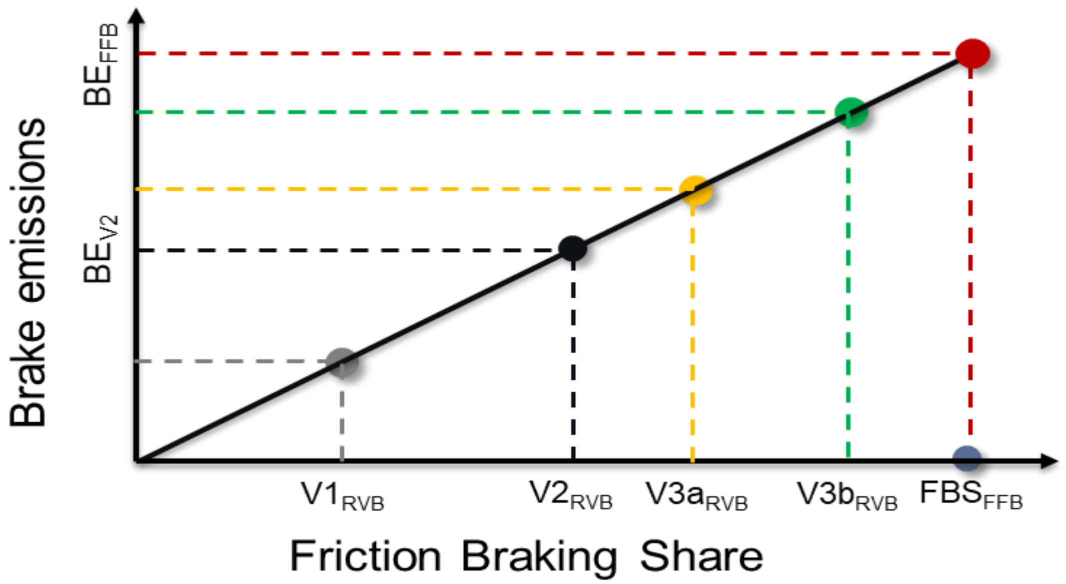
"FFB" = Test inertia and vehicle characteristics of the actual vehicle considering driving resistances. No recuperation



JRC'S PROPOSAL – EMISSIONS CALCULATION

"Real vehicle" behavior: The method foresees the application of constant coefficients for four vehicle categories (V1. PEV; V2. OVC-HEV; V3. NOVC-HEV sub-divided in V3a. "Regular"- and V3b. "Mild"-Hybrids).

"FFB" = Test inertia and vehicle characteristics of the actual vehicle considering driving resistances. No recuperation



"RVB" = "Real vehicle behaviour": Interpolated emission value, **not** measured! Depends on the vehicle category

- ✓ The calculation of the PM/PN emission factors for the given brake is done by multiplying the PM/PN emissions measured at the FFB scenario times the defined coefficient for the vehicle category on which the tested brake is mounted on;
- ✓ The coefficients for each vehicle category represent the expected friction brake energy share over the overall energy demand. The higher the level of "electrification", the lower the coefficient shall be (Friction Brake Share: V1 < V2 < V3a < V3b).

JRC'S PROPOSAL – COEFFICIENTS (Method)

- ✓ The proposal foresees the application of constant coefficients for four vehicle categories (V1. PEV; V2. OVC-HEV; V3. NOVC-HEV sub-divided in V3a. "Regular"- and V3b. "Mild"-Hybrids). The coefficients represent the friction brake energy share over the overall energy brake demand;
- ✓ Full vehicle chassis dyno tests over the WLTC exhaust cycle were used to calculate the friction brake share over the overall energy demand. The calculation is based on an energy balance at wheels-level over the test cycle*.

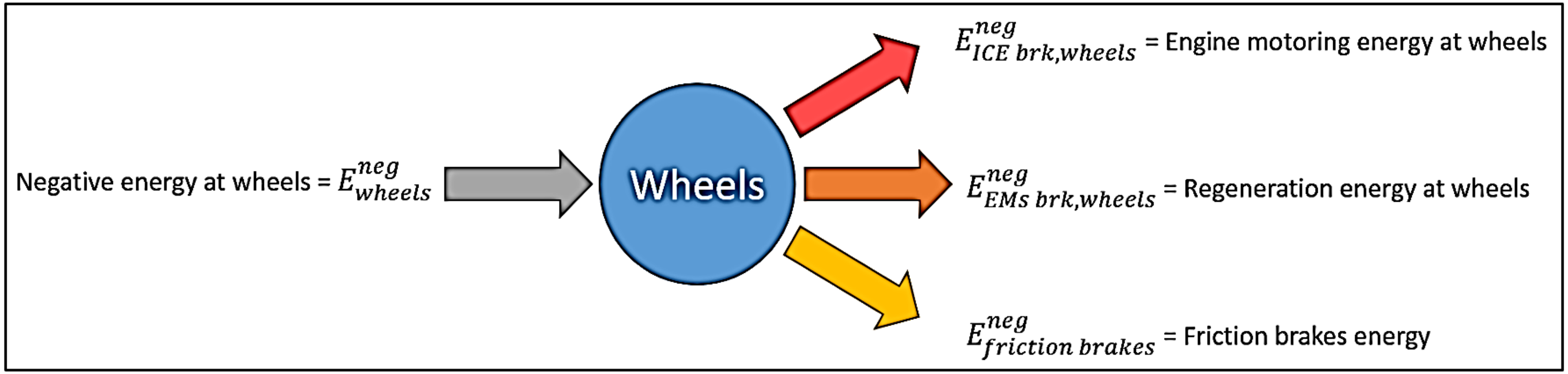


Figure 1. Schematic of the energy balance at the wheels

Vehicle resistances, ICE motoring, Electric Machine(s) energy recuperation, and Friction Braking are considered.

JRC'S PROPOSAL – COEFFICIENTS (JRC Results)

Vehicle	Type	Battery capacity [kWh]	Initial SOC (%)	Cycle	Engine motoring energy [%]	Regeneration braking energy [%]	Friction brakes energy [%]
BEV1	BEV	77	75	WLTC	0.0	85.3	**14.7**
BEV1	BEV	77	62	WLTC	0.0	85.5	**14.5**
BEV2	BEV	82	100	WLTC	0.0	91.5	**8.5**
PHEV1	PHEV	13	28	WLTC	2.9	79.5	**17.6**
PHEV2	PHEV	13.1	N/A	WLTC	2.5	72.2	**25.2**
PHEV3[1]	PHEV	16	100	WLTC	0.0	86.1	**13.9**
MHEV1	MHEV	0.17	45	WLTC	13.4	38.6	**48.0**
MHEV2	MHEV	0.48	73	WLTC	3.5	43.8	**52.8**

[1] ***Brake simulated by a stakeholder assuming full SOC at the beginning***

- Friction share increases going from PEV to Mild-hybrids – Data for "Regular HEV" have not yet been finalized;

- JRC data for PEV range between 8-15%, for OVC-HEV between 14-25%, and for "Mild-Hybrids" between 48-53%. This is for the WLTC exhaust cycle.

JRC'S PROPOSAL – COEFFICIENTS (Cycle shift)

As a next step the friction share over the WLTC exhaust cycle shall be extrapolated to the WLTP-Brake cycle to reflect the GTR testing conditions.

Vehicle	Type	Battery capacity [kWh]	Initial SOC (%)	Cycle	Engine motoring energy [%]	Regeneration braking energy [%]	Friction brakes energy [%]
PHEV1	PHEV	13	28	WLTC	2.9	79.5	**17.6**
PHEV1[1]	PHEV	13	N/A	WLTP brake	0.0	76.0	**24.0**
PHEV3[2]	PHEV	16	100	WLTC	0.0	86.1	**13.9**
PHEV3[2]	PHEV	16	100	WLTP brake	0.0	82.9	**17.1**

[1] Brake simulated by a stakeholder assuming full SOC at the beginning

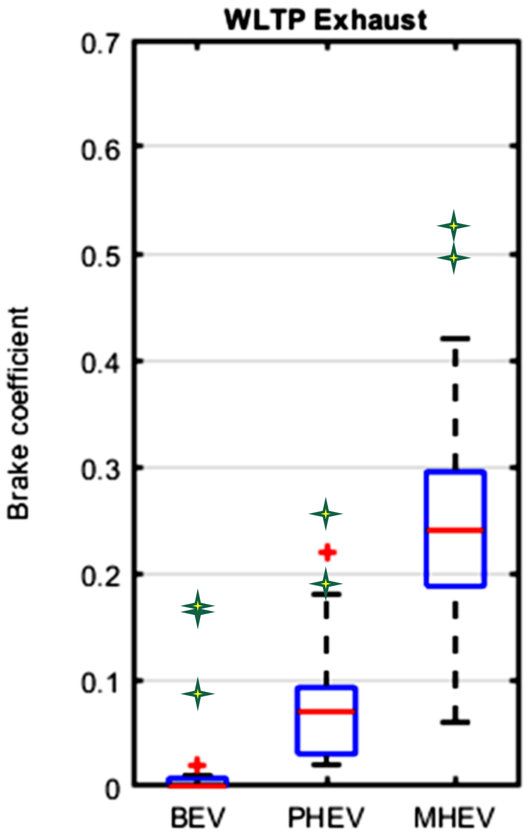
[2] Brakes simulated by a stakeholder assuming full SOC at the beginning

- Friction share increases shifting from the regulated WLTC exhaust cycle to the WLTP-Brake cycle by 23-36% for two PHEVs;

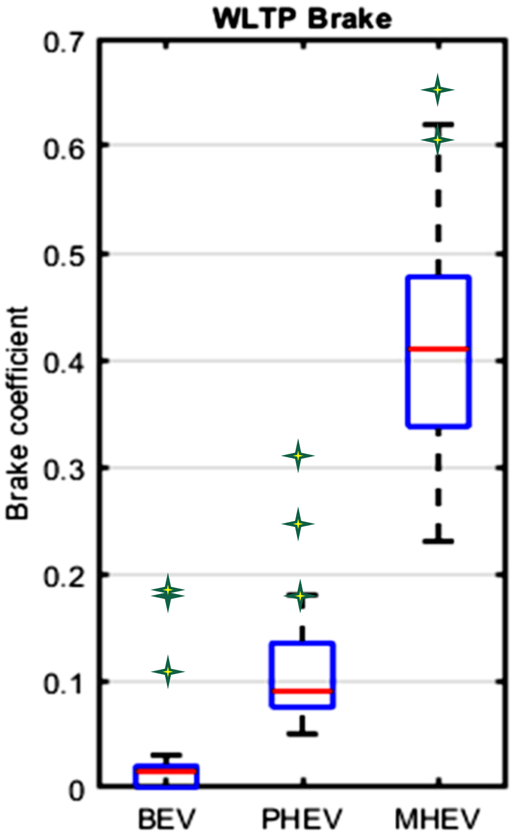
- JRC does not have chassis dyno data with the WLTP-Brake cycle. More data from the stakeholders (simulations included) are required.

JRC'S PROPOSAL – COEFFICIENTS (OICA Results)

As a next step, data from other stakeholders was requested. OICA collected data from 6 OEMs and 55 vehicles and submitted them to the TF4 Meeting #21.



Values from JRC measurements



Values from JRC measurements "fitted" to the WLTP-Brake cycle

- ✓ JRC data on the WLTC exhaust are at the higher end of the OICA data for OVC-HEV;
- ✓ Higher values for "Mild-Hybrids" in the NOVC-HEV category. There is a significant difference in PEV;
- ✓ The "fitted" JRC data assuming a 25% correction to account for the differences in the cycle are at the higher end of the OICA data for OVC-HEV and NOVC-HEV.
- ✓ A significant difference in PEV category still remains.

JRC'S PROPOSAL – COEFFICIENTS (Proposal)

Vehicle Category	Proposed Coefficients
PEV	**0.17-0.19**
OVC-HEV	**0.30-0.32**
NOVC-HEV ("Regular")	**Under elaboration**
NOVC-HEV ("Mild")	**0.60-0.65**

- ✓ *Coefficients have been elaborated considering the worst performing vehicle in each category and applying a 25% correction to take into account the change of cycle;*
- ✓ *For the time being, JRC proposes a margin in the coefficients (from-to) due to non-availability of many data points – the final version shall include a unique value for each vehicle category;*
- ✓ *Additional data – ideally using the WLTP-Brake cycle – would be necessary to further fine-tune the proposed coefficients – intention to finalize the values by 15.12.*

JRC'S PROPOSAL – TESTING SEQUENCE

- ✓ Step 1: The brake is tested over Trip #10 of the WLTP-Brake cycle to define its cooling settings – Test inertia and vehicle characteristics of the actual vehicle where the tested brake is mounted on;

- ✓ Step 2: The brake undergoes bedding applying the cooling settings from Step 1 – Five WLTP-Brake cycles with test inertia and vehicle characteristics of Step 1;

- ✓ Step 3: The brake is tested over the WLTP-Brake cycle to measure the full-friction PM/PN emissions. Test according to the full-friction brake protocol with test inertia and vehicle characteristics of Step 1;

- ✓ Step 4: The Final brake PM/PN emission factors are calculated from the values of the previous step with the application of the defined coefficients. For example, a brake with FFB PM_{10} emissions of 5 mg/km:
    - RVB PM_{10} = 5 mg/km * 0.17 = 0.85 mg/km if mounted on a PEV
    - RVB PM_{10} = 5 mg/km * 0.30 = 1.5 mg/km if mounted on a OVC-HEV
    - RVB PM_{10} = 5 mg/km * 0.62 = 3.1 mg/km if mounted on a Mild-Hybrid

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JRC'S PROPOSAL – RESPONSE TO NEEDS

- ✓ The current method provides a simplified approach that fully relies on the existing protocol (GTR formal document);
- ✓ The current method does not need to consider parameters on a case by case basis (battery level, recharging frequency) – Different vehicle categories have different coefficients but the main principle remains the same;
- ✓ The current proposal is fully transparent and accessible to third party testing – The full-friction scenario test is identical in all laboratories with and w/o access to proprietary data;
- ✓ The current method is applicable to the currently available dyno setups as it practically does not require regen capabilities;
- ✓ The current method allows for a straightforward definition of the brake families based on the friction energy dissipated;

The current method is proposed for the GTR to be adopted in January as is – further refinement can be investigated with the continuation of TF4 after the adoption.

Thank you

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