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PARTICLE MEASUREMENT PROGRAMME
PMP-IWG

TASK FORCE 3 - ILS-3 Summary

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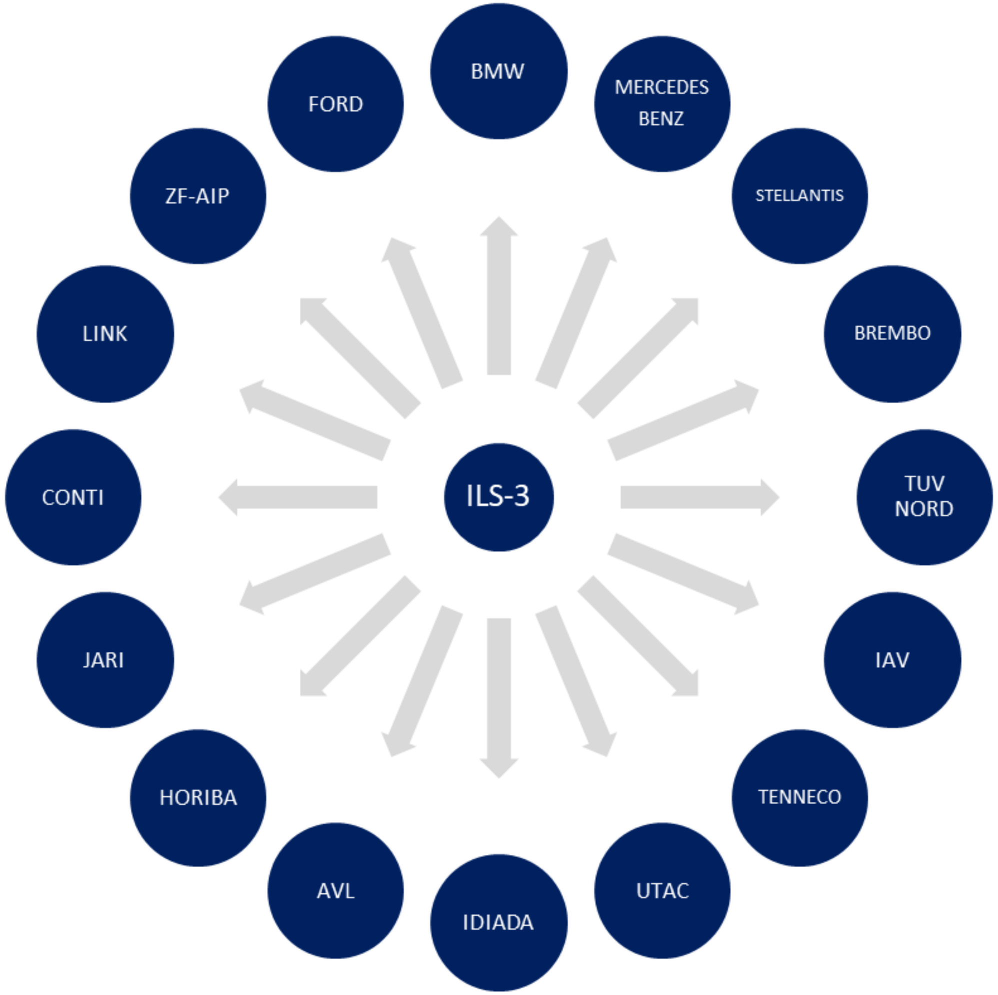
Joint
Research
Centre

ILS3 ORGANIZATION – PARTICIPANTS



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ILS3 PLAN & EXECUTION SUMMARY

	BMW Brake M1 Test	BMW Brake M2 Test	FORD Brake M1 Test	FORD Brake M2 Test	JLR Brake M1 Test	JLR Brake M2 Test
Lab-A	√	√	√	√	√	√
Lab-B						
Lab-C	√	√	√	√	√	√
Lab-D	√	√	√	√	√	√
Lab-E	√	√	√	√	√	√
Lab-F	√	√	√	√	√	√
Lab-G	√	√	√	√	√	√
Lab-H						
Lab-I	√	√	√	√	√	√
Lab-J	√	√	√	√	√	√
Lab-K	√	√	√	√	√	√
Lab-L	x	x	√	√	√	√
Lab-M	√	√	√	√	√	√
Lab-N	√	√	√	√	√	√
Lab-O	√	√	√	√	√	√
Lab-P	√	√	√	√	√	x

Withdrawn | Not-compliant | Completed

96/96
Completed withdrawn labs included
100%

81/84
Completed withdrawn labs not included
100%

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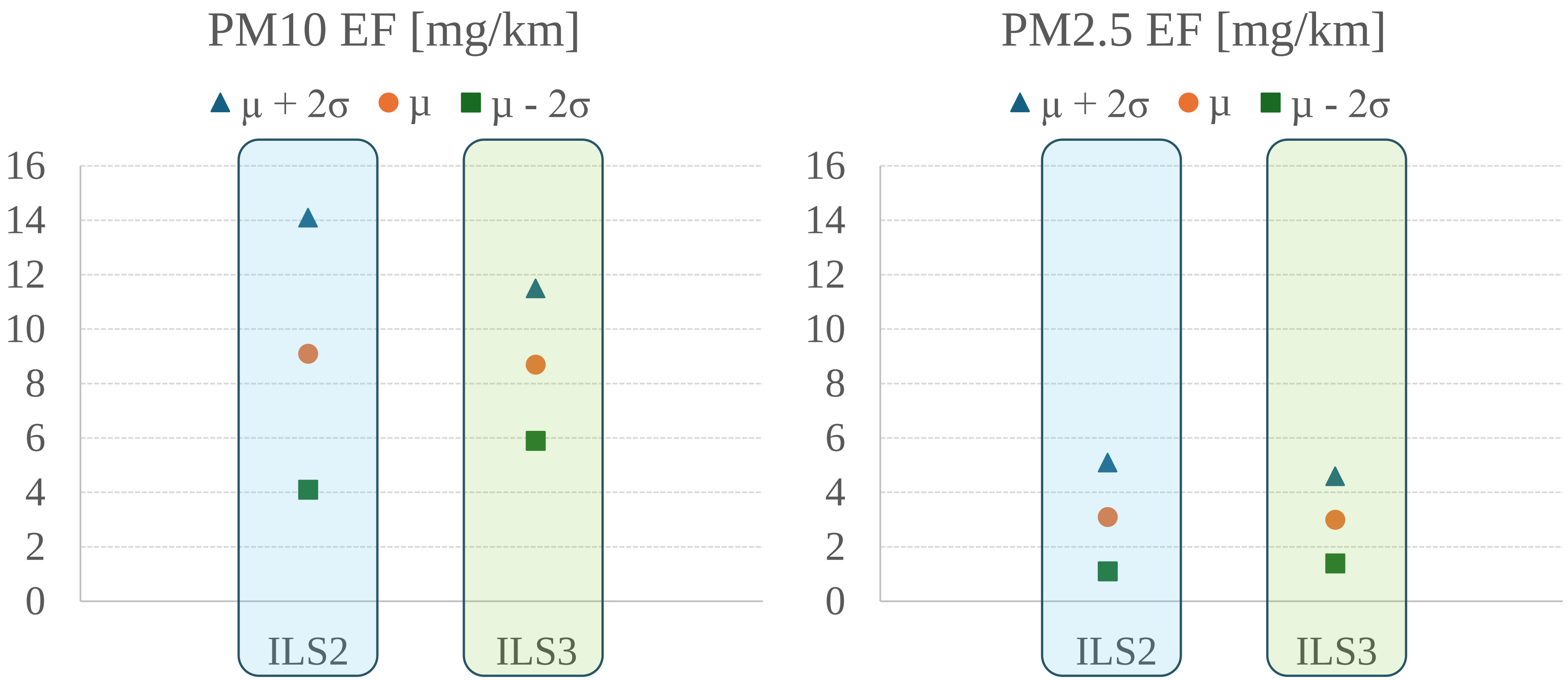
REFERENCE BRAKE: BMW X5

BMW X5 front brake was tested in both ILS2 and ILS3



ILS2:
5 labs, 15 datapoints

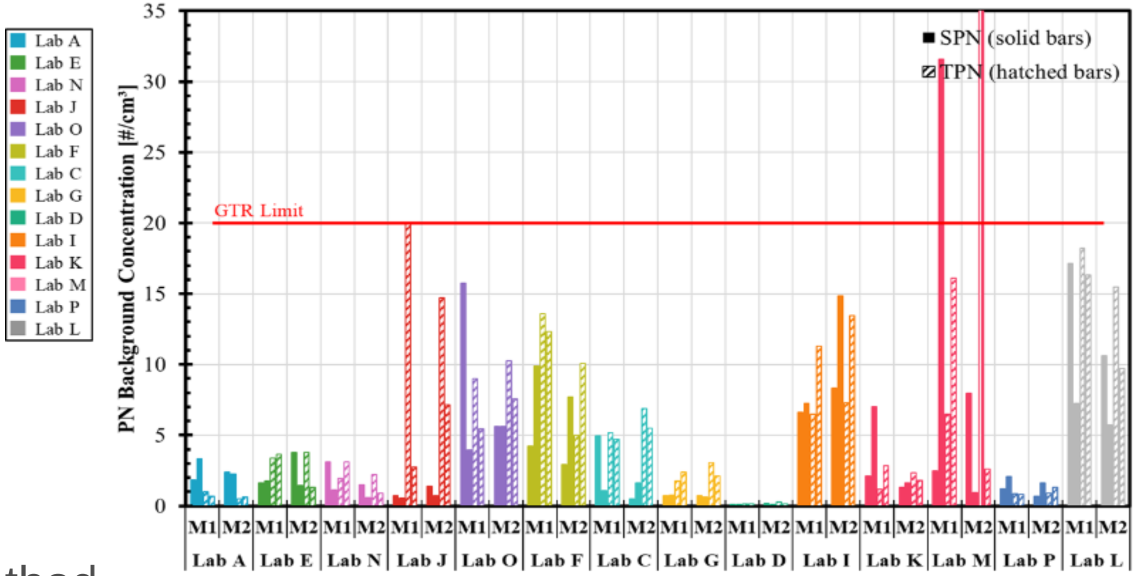
ILS3:
13 labs, 75 datapoints

✓ Both increased datapoints and harmonized testing could have improved ILS3 results

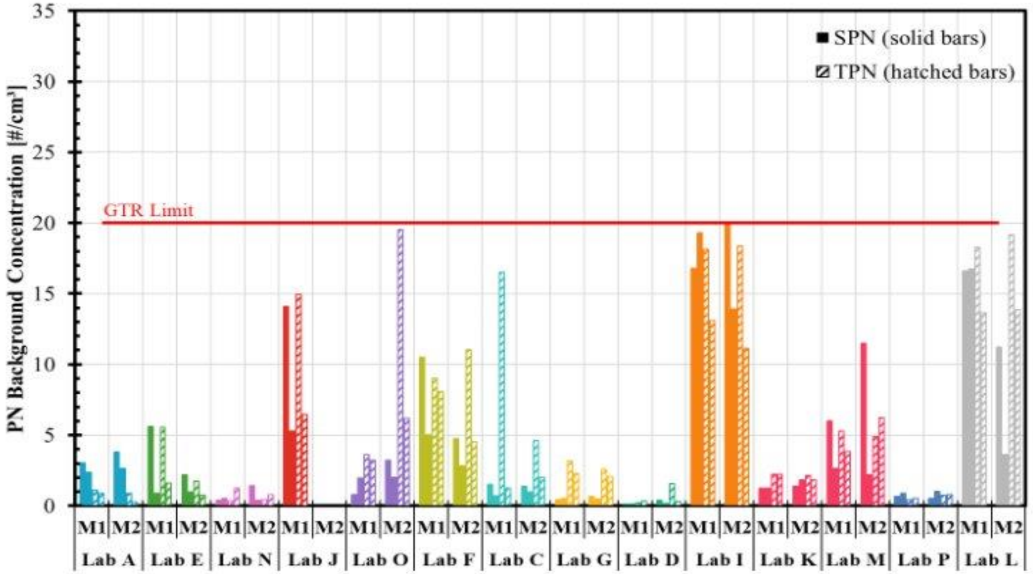
PN BACKGROUND [#/cu.cm]

1st bar – pretest
2nd bar – post test

PUMA



JLR



Method

- Measure average background PN concentration and integrate over the measured duration

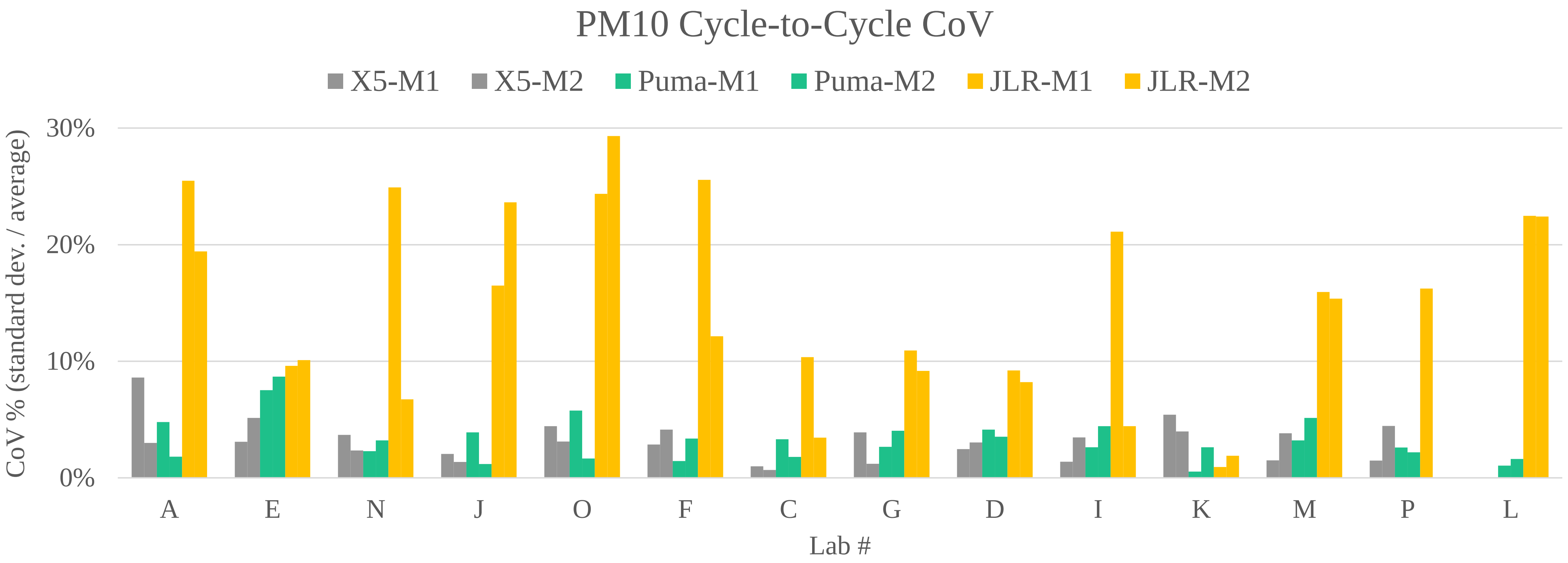
Exclusion

- Puma: Labs M, P, data unavailable JLR: Lab J-M2, data unavailable

PN pretest background less than GTR limit (20 #/cu.cm)

PM10 CYCLE-TO-CYCLE VARIATIONS

Intra-lab cycle-to-cycle CoV for M1 and M2. Three brakes – BMW X5 | Ford Puma | JLR



- ✓ Intralab repeatability of PM10 for BMW X5 and Ford Puma are similar (Avg 3%)
- ✓ PM10 CoV for JLR NAO brake is about 5x more than for X5 and Puma brakes

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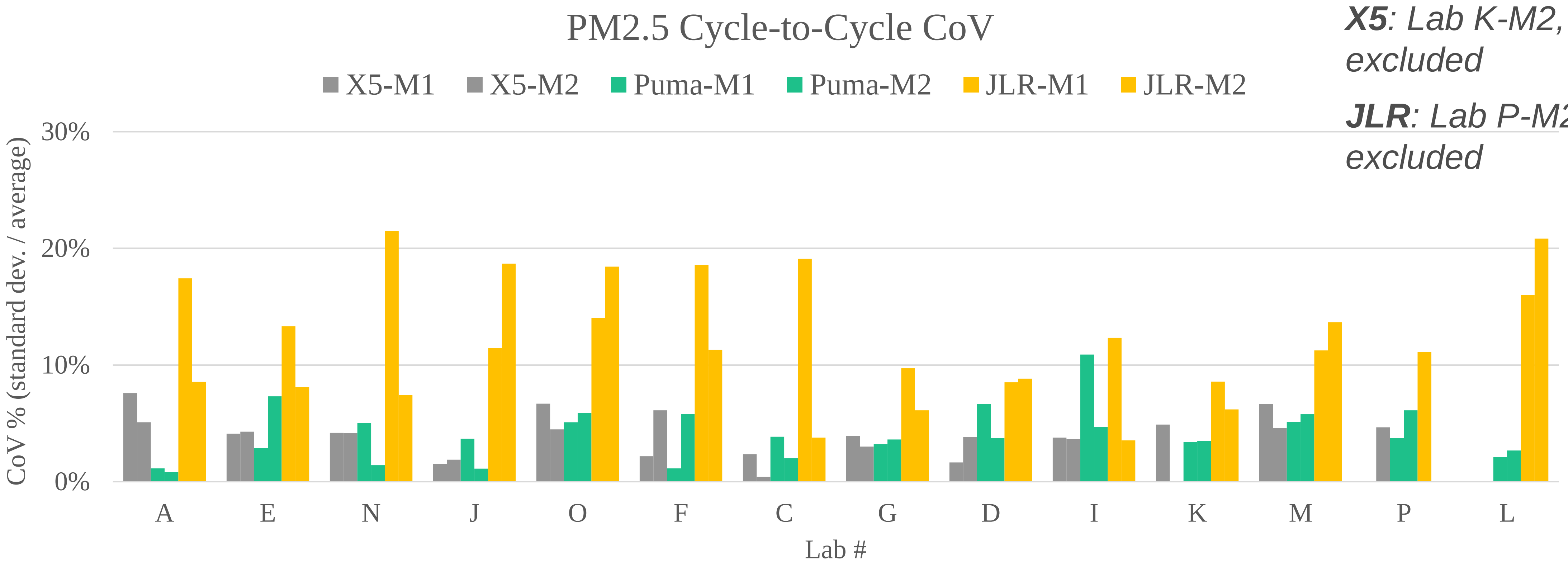
PM2.5 CYCLE-TO-CYCLE VARIATIONS

Intra-lab cycle-to-cycle CoV for M1 and M2. Three brakes – BMW X5 | Ford Puma | JLR



***X5**: Lab K-M2, P-M1 excluded*

***JLR**: Lab P-M2 excluded*

- ✓ Intralab repeatability of PM10 for BMW X5 and Ford Puma are similar (Avg 4%)
- ✓ PM2.5 CoV for JLR NAO brake is about 3x more than for X5 and Puma brakes

SUMMARY ON PM EF

PM10			
	BMW X5 ILS3 [13 labs - 75 points]	FORD PUMA ILS3 [14 labs - 82 points*]	JLR BRAKE ILS3 [14 labs - 79 points**]
PM10 [mg/km]	8.7	4.7	1.4
StDev	1.4	0.45	0.4
CoV	**15.8%**	**9.4%**	**27.7%**
PM2.5			
	BMW X5 ILS3 [13 labs - 75 points]	FORD PUMA ILS3 [14 labs - 82 points*]	JLR BRAKE ILS3 [14 labs - 79 points**]
PM2.5 [mg/km]	3.0	1.4	0.7
StDev	0.8	0.35	0.2
CoV	**26.2%**	**25.2%**	**27.9%**

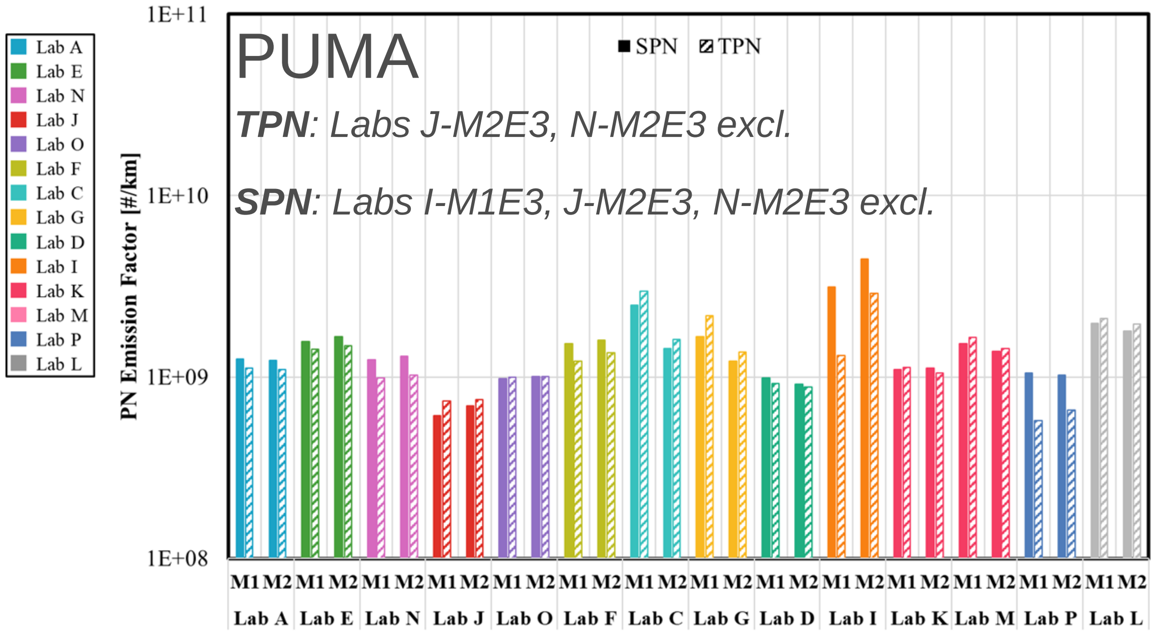
** Two cycles are self declared as invalid by labs J and N*

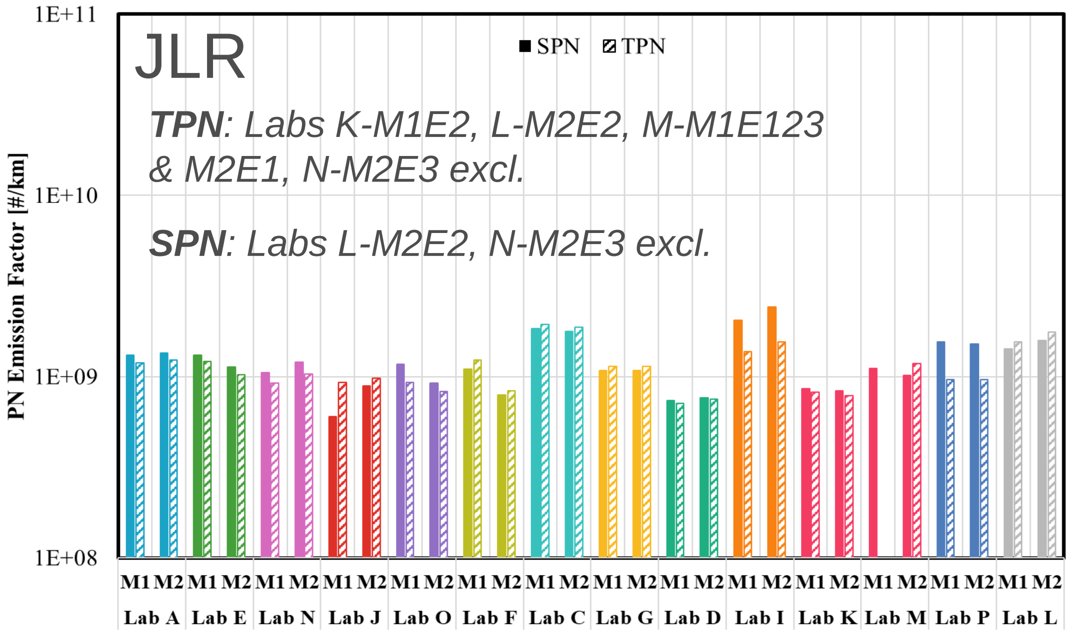
*** Two cycles are self declared as invalid by labs L and N*

*** Three cycles are self declared as invalid by lab P*

- ✓ PM10 CoV ranges from ≈10% to 30%
- ✓ PM2.5 CoV is almost constant (≈25%)

PN EFs: FORD PUMA AND JLR BRAKES

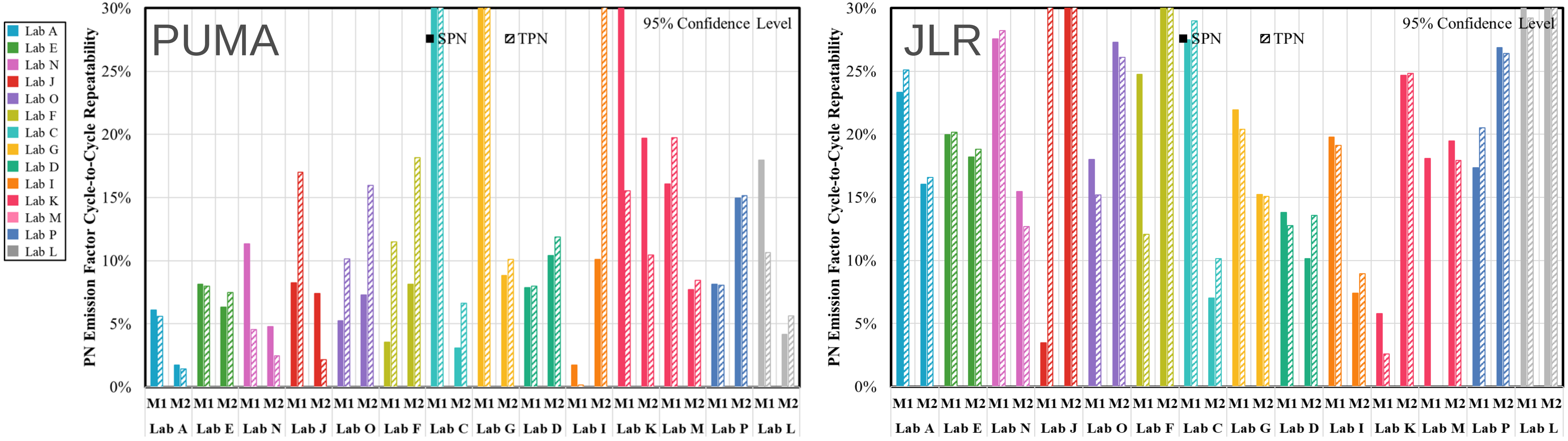




PN EFs (Average ± 2*sigma)

	FORD PUMA [14 labs - 81 points]	JLR BRAKE [14 labs - 77 points]
TPN10 [#/km]	1.35E+09 ± 1.14E+09	1.14E+09 ± 6.39E+08
SPN10 [#/km]	1.50E+09 ± 1.47E+09	1.23E+09 ± 7.99E+08

PN CYCLE-TO-CYCLE REPEATABILITY



95% Confidence Level		
	FORD PUMA [14 labs - 81 points]	JLR BRAKE [14 labs - 77 points]
TPN10	16.3%	21.6%
SPN10	12.0%	20.5%

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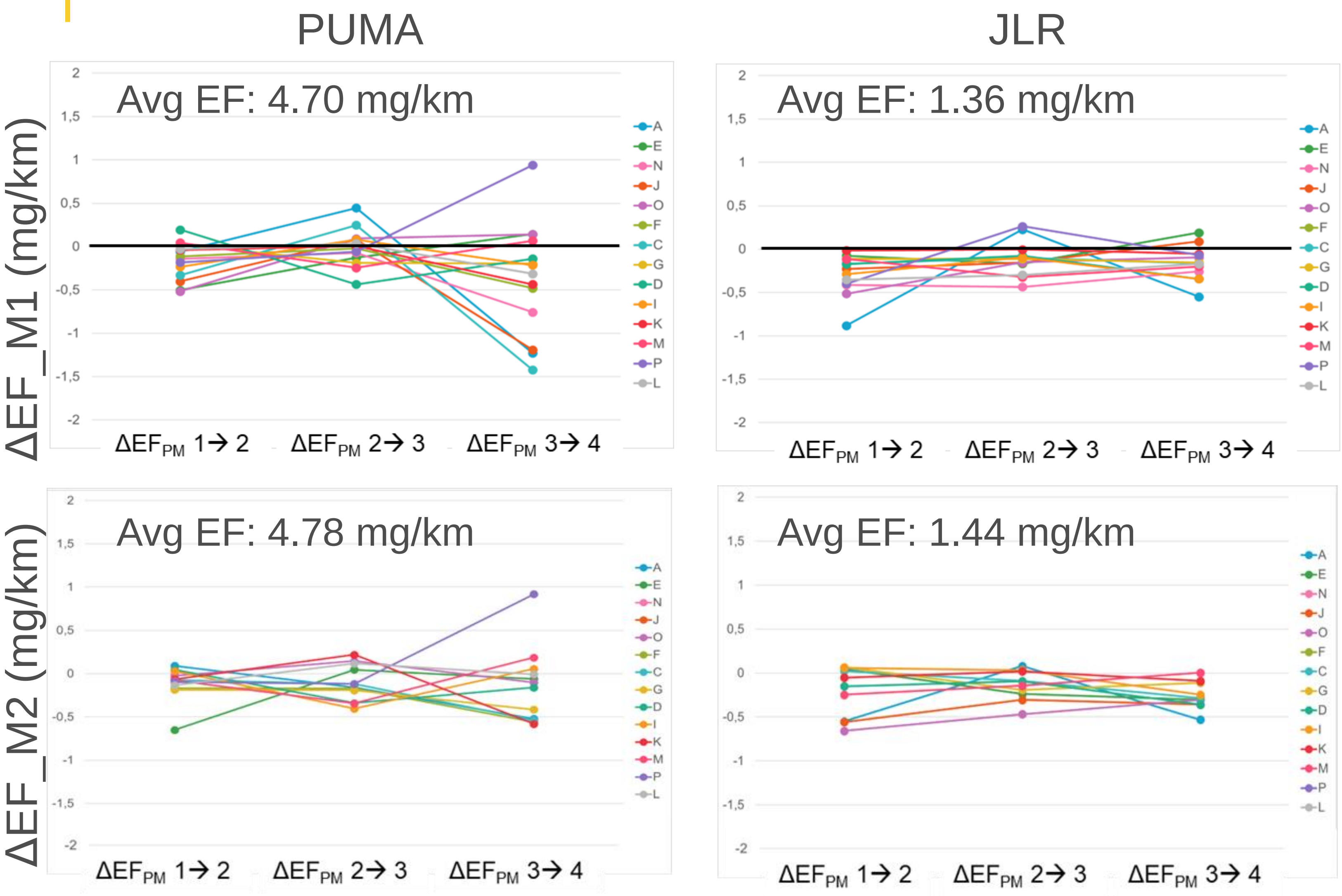
PM10 EF: WITH VARIABLE OR CONSTANT AIRFLOW



Puma:

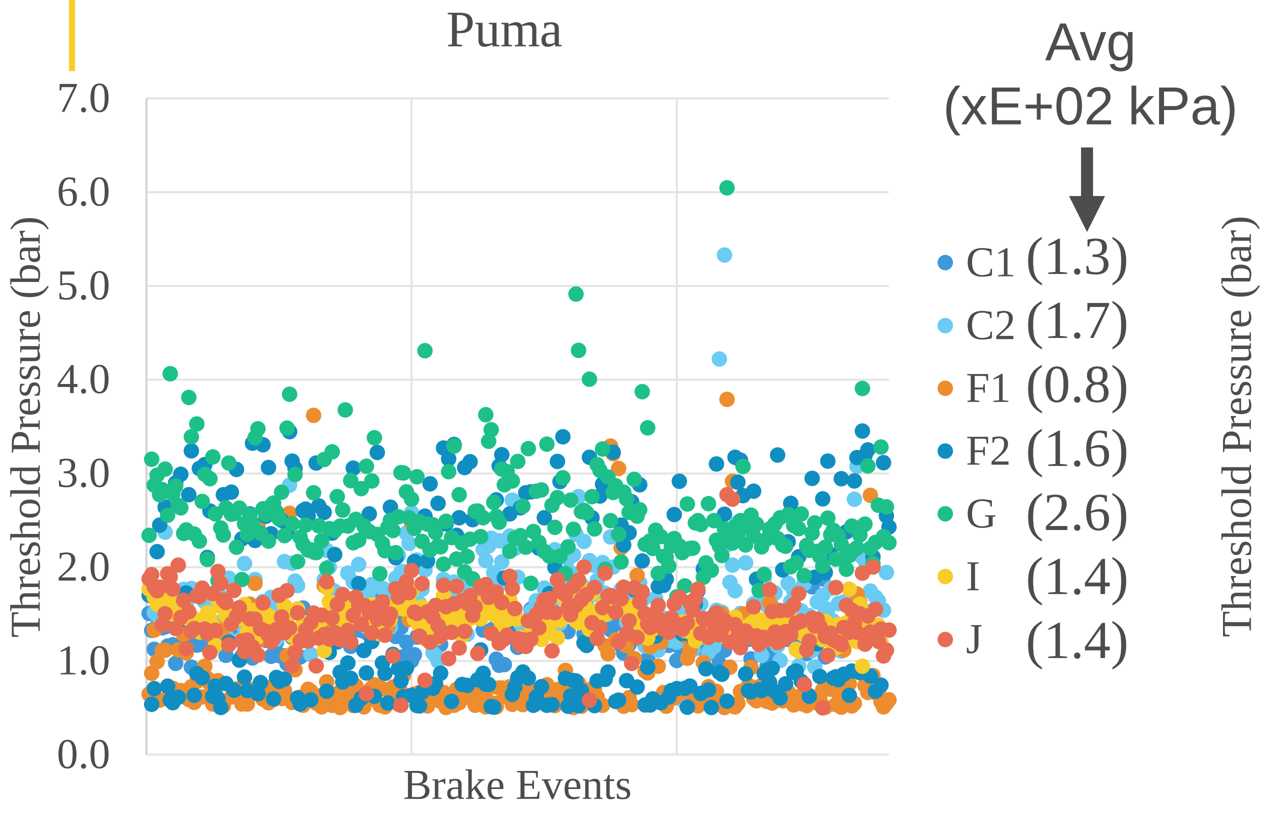
- Labs C, A, J, N, show a 15%-30% EF reduction in E3-E4 compared to E2-E3.
- Lab P E3-E4, 20% EF gain

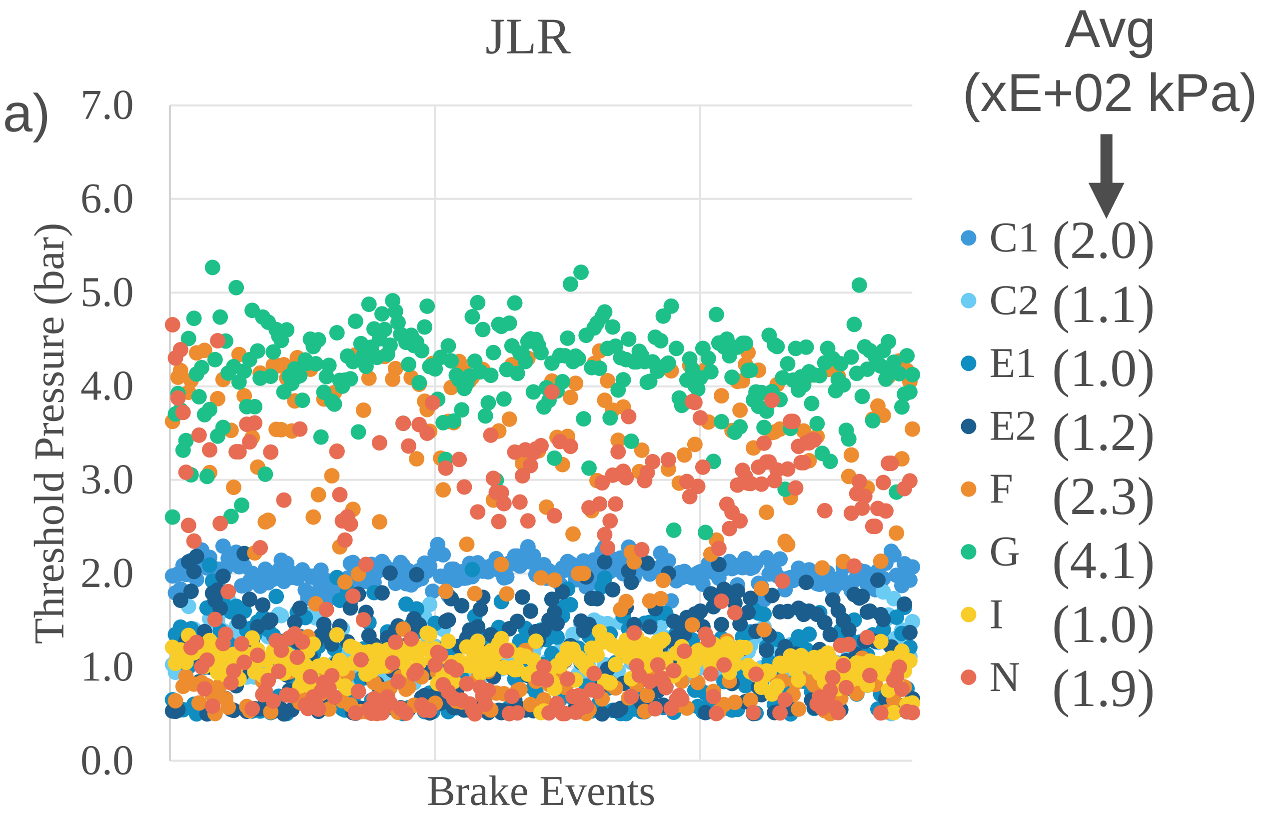
JLR:

- No clear trend from E1-3 to E4

M1-to-M2 results are not repeatable to clearly attribute airflow to the EF change

THRESHOLD PRESSURE (DISC BRAKES)





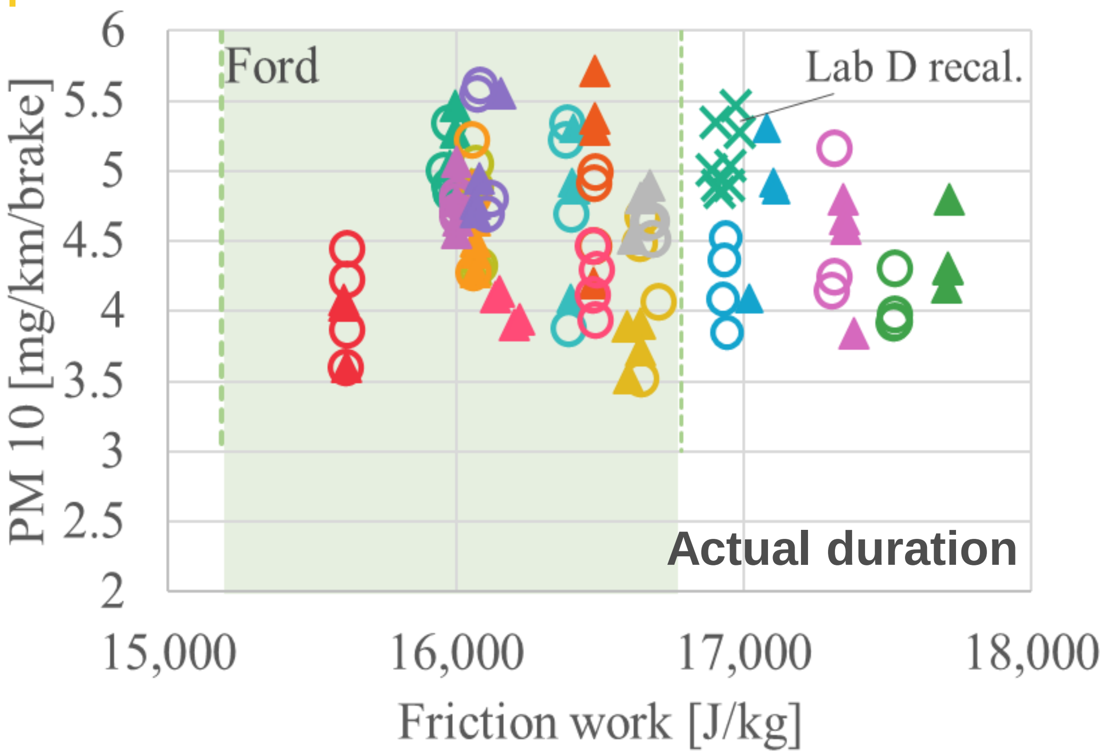
Mean	150 kPa
Sigma	51 kPa

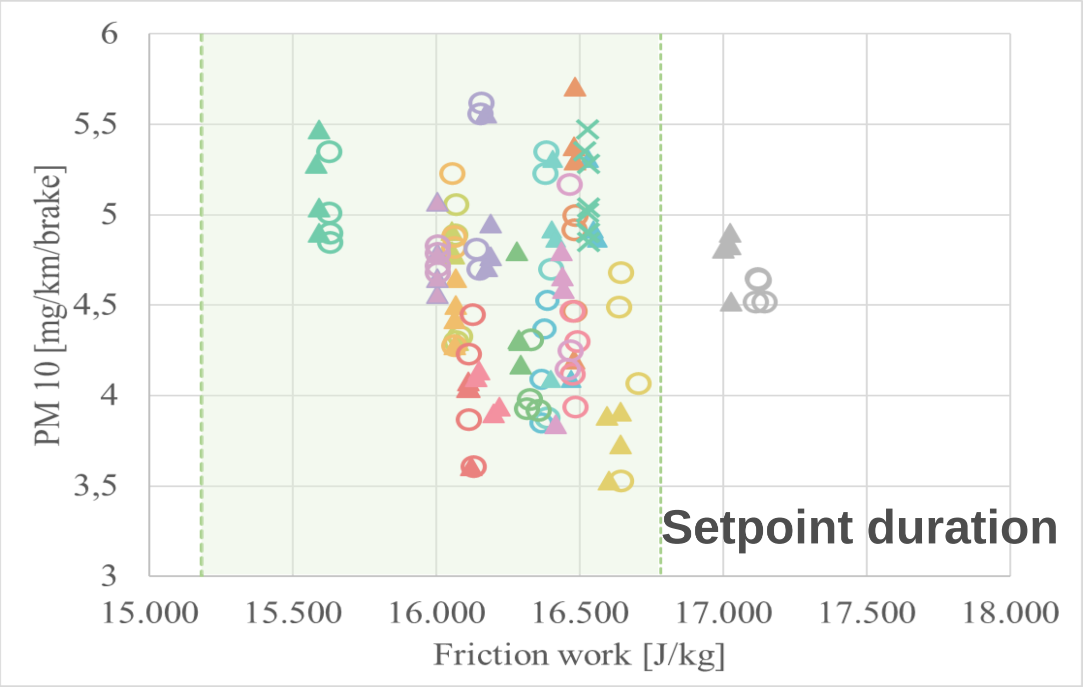
Mean	180 kPa
Sigma	98 kPa

Mean -1*Sigma ≅100 kPa

✓ **Lab G shows exceptionally high threshold pressure for both brakes**

FRICTION WORK (ACTUAL v. SETPOINT DURATION)

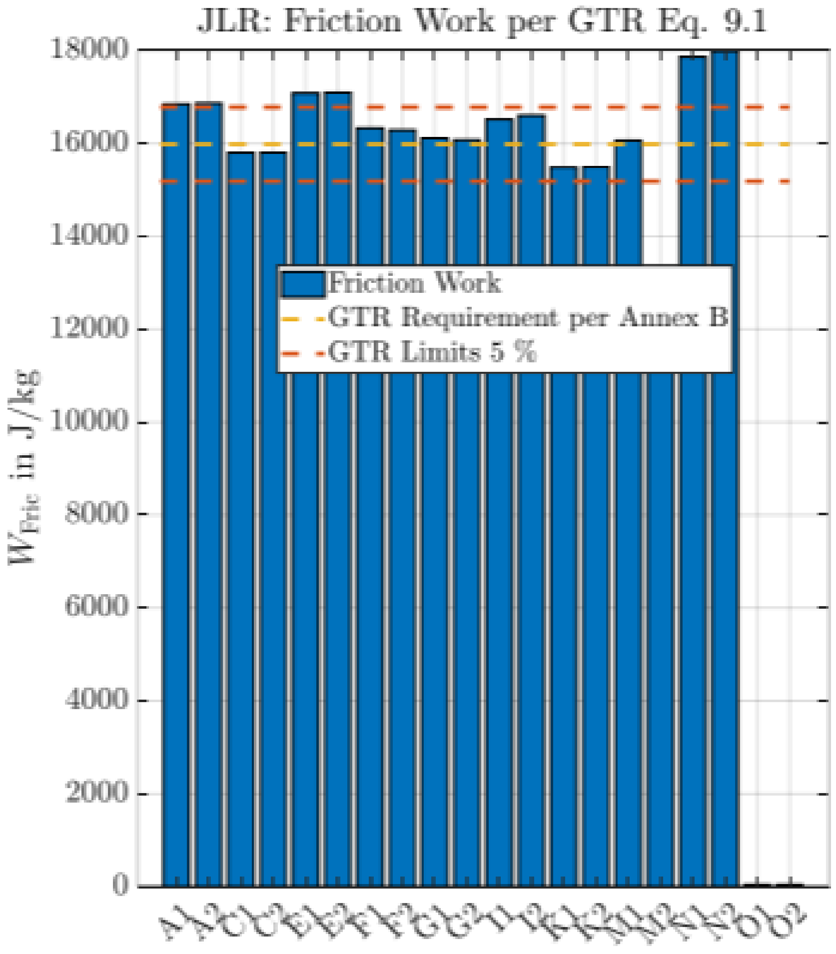


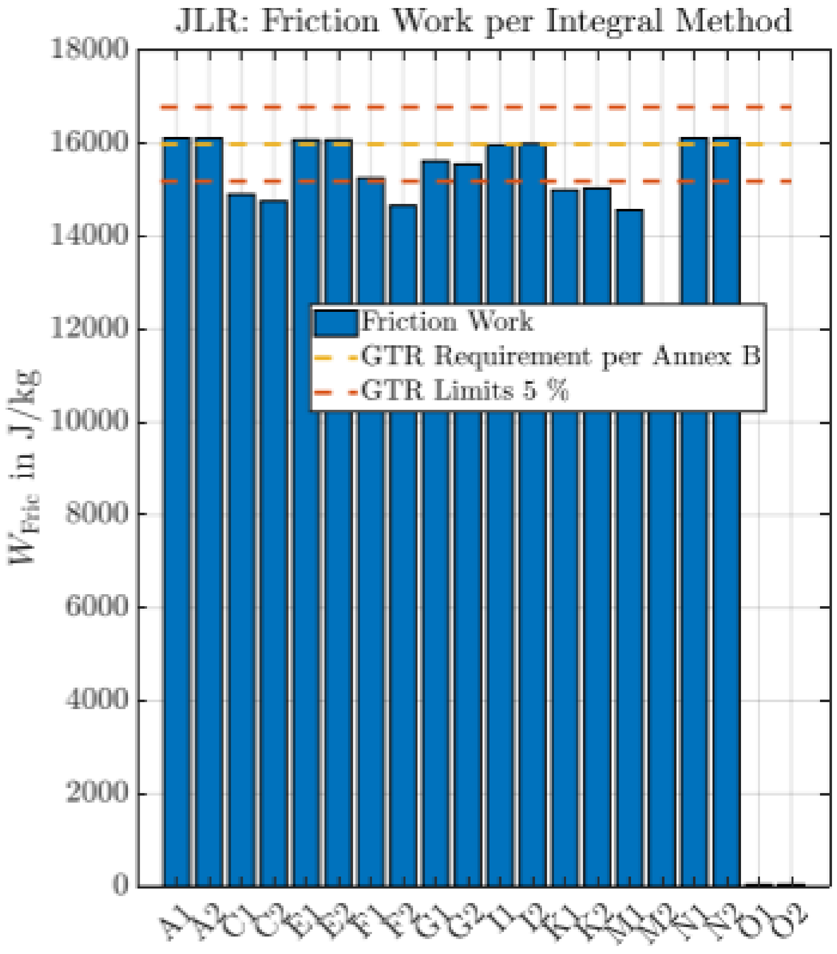


- With setpoint duration, friction work for almost all labs is within the GTR limits
- Lab L values go beyond limit with setpoint duration in contrast to measured duration

Usage of different duration values in different labs

FRICTION WORK CALCULATION METHODS





The integral method using nominal speed for brake detection points gave higher accuracy values

PROPOSAL FOR FRICTION WORK [9.4.3.h]

(h) The testing facility shall calculate the specific friction work for each brake event using the the fast actual torque signal and the fast rotational speed signal of the test system. The integration shall start 1.0s before the brake deceleration event starts until 1.0s after the brake deceleration event ends according to Equation 9.1:

$$w_{f,n} = \frac{2 \times \pi}{60} \cdot \frac{1}{WL_t} \cdot \int_{t=t_{start,nom,n}-1.0s}^{t_{end,nom,n}+1.0s} f(t) \cdot \tau(t) \cdot dt \qquad \text{(Eq. 9.1)}$$

~~$w_f = (2 \times \pi/60) \times f \times \tau_{brake} \times t_{brake}/WL_t$ (Eq. 9.1)~~

Where:

$w_{f,n}$ is the specific friction work of the n[th] brake deceleration event in J/kg;

WL_t is the test (or applied) wheel load in kg per Table 8.1;

$t_{start,nom,n}$ is the start time of the n[th] nominal brake deceleration event in s;

$t_{end,nom,n}$ is the end time of the n[th] nominal brake deceleration event in s;

f(t) is the fast rotational speed signal in 1/min;

τ_{brake} is the fast brake torque signal in Nm;

Both, brake deceleration event start time and brake deceleration end time for each event is identified based on fast nominal linear speed.

Calculate the acceleration based on the fast nominal speed.

A specific brake event starts at the first time this acceleration value exceeds 0.25 m/s^2 and ends at the first time this acceleration value falls below 0.25 m/s^2.

PROPOSAL FOR EBF PARAMETERS CALC. [13.1]

Regardless of the sampling rate, in the Event-Based File the parameters shall be reported for each individual brake decelaration event. . All evaluations for use in EBF file - except the calculation of friction work values (see 9.4.3 (h)) - shall be based on the actual brake deceleration event.

A specific actual brake deceleration event starts at the first time the fast actual torque exceeds 15% of the target torque of this specific brake event. The actual brake deceleration event ends when the fast actual torque falls below 15% of the target torque.

Both actual brake deceleration event start time as well as actual brake deceleration end time for each event is identified based on fast actual torque speed. The actual brake event starts at the first time the actual torque exceeds 15 % of the target torque of the brake event. The actual brake event ends at the first time the actual target torque value falls below 15% of the target torque.

The target torque of a specific target torque can be calculated according to Eq X.XX.

$$M_{Target,j} = m_{wheel\ load} \times r_{dyn} \times \frac{v_{start,Target,j} - v_{end,Target,j}}{3.6 \times t_{duration,j}} \quad \text{Eq X.XX}$$

$M_{Target,j}$	nominal torque of the specific brake event given by WLTP Brake cycle [Nm]
$m_{wheel\ load}$	applied dynometer wheel load [kg]
r_{dyn}	rolling radius [m]
$v_{start,Target,j}$	velocity at start point given by WLTP Brake cycle [km/h]
$v_{end,Target,j}$	velocity at end point given by WLTP Brake cycle [km/h]
$t_{duration,j}$	duration of brake event given by WLTP Brake cycle [s]

Some of the parameters reported in the Event-Based file are defined by the actual brake event start and end time as they represent their instantaneous values at these timestamps (i.e. Time of Stop, Stop Duration, Initial Brake Temperature, Final Brake Temperature). The rest of the parameters shall be averaged (distance- or timebased) over the brake event to report a unique value for each parameter. The averaging of these parameters shall be performed using the 250 Hz data sampled between the actual start and end point of the brake event.

DEFINITION UPDATES FOR NEW PROPOSALS

3.1.25. "*Average by time*" means the averaging method for a given measurand through a brake event. The resultant value yields the same result as the integration between two instances (threshold and end of level reached) divided by the duration between the corresponding points.

To remove average-by-time definition from Paragraph 3.1

3.4.10. "Nominal *Brake deceleration event*" means a measurable period during which the nominal linear speed decreases at a known rate to a predetermined release speed during the cycle. The nominal deceleration event is identified using the fast nominal linear speed signal as per paragraph 9.4.3 (i).

3.4.11. "Actual brake deceleration event" means a measurable period during which the linear speed decreases at a known rate to a predetermined release speed during the cycle. The actual brake deceleration event is identified using the fast actual torque signal as per paragraph 13.1.

From >15% to <15% of target torque

3.4.254. "Actual *Peak brake temperature*" means the highest brake disc or drum temperature measured during a given brake event.. It is determined during data evaluation as the maximum of the fast actual brake temperature during a given actual brake deceleration event.

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DEFINITION UPDATES FOR NEW PROPOSALS

3.4.1516. "Actual Initial speed" means the speed of the vehicle at the actual start of a brake deceleration event. It is determined during data evaluation by averaging the fast actual linear speed value from 1.0s to 0.5s before the actual brake deceleration event starts.

3.4.1617. "Actual Release speed" means the speed of the vehicle at the actual end of a brake deceleration event. It is determined during data evaluation by averaging the fast actual linear speed value from 0.5s to 1.0s after the actual brake deceleration event has ended.

3.4.221. "Actual Initial brake temperature" means the bulk temperature of the brake disc or brake drum at the start of a given brake event during the WLTP-Brake cycle. It is determined during data evaluation by averaging the fast actual brake temperature from 1.0s to 0.5s before the actual brake deceleration event starts.

3.4.232. "Actual Final brake temperature" means the bulk temperature of the brake disc or brake drum at the end of a given brake event during the WLTP-Brake cycle.. It is determined during data evaluation by averaging the fast actual brake temperature from 0.5s to 1.0s after the actual brake deceleration event has ended.

Table 13.1

Actual initial speedInitial Brake Speed Measured	-	km/h	1	The measured linear speed at the beginning of the actual brake deceleration event calculated as defined in 3.4.16.
Actual release speedRelease Speed Measured	-	km/h	1	The measured linear speed at the end of the actual brake deceleration event calculated as defined in 3.4.17
Actual Initial Brake Temperature	IBT	°C	1	Brake temperature at the beginning of the actual brake deceleration event measured as defined in paragraph 3.4.22
Actual Final Brake Temperature	FBT	°C	1	Brake temperature at the end of the actual brake deceleration event measured as defined in paragraph 3.4.23

DEFINITION UPDATES FOR NEW PROPOSALS

Table 13.1

Rotational Speed	f	rpm	1	Time-averaged rotational brake speed registered by the brake dynamometer. The rotational speed sampled during the brake event at 250Hz shall be reported at the individual brake event level as time averaged. Averaging shall be performed between actual deceleration event start and actual brake deceleration end of the brake event.
Brake Torque – Distance Averaged	-	Nm	1	Distance averaged brake torque … Averaging shall be performed between actual deceleration event start and actual brake deceleration end of the brake event.

Specific Friction Work	$\|W_{f,n}\|$	J/kg	1	Specific friction work of the brake deceleration event calculated as defined in paragraph 9.4.3 (h)

Same changes apply to
Brake Pressure &
Friction coefficient/brake effectiveness

All corresponding text changes are also reflected in Table 13.6 GTR report

OTHER DEFINITION PROPOSALS

3.1.23. "~~*Friction coefficient*~~*Brake effectiveness*" means the ratio between the total tangential force and the ~~normal~~actuation force ~~acting~~ between the brake pads and the disc or between the brake shoes and the drum. T~~For a disc brake, t~~he ~~apparent friction coefficient~~brake effectiveness value from the brake under testing is a function of braking torque, hydraulic pressure, effective brake radius, and the piston area. The brake effectiveness ~~apparent coefficient of friction~~ is a calculated (mathematical) value and is not directly measurable. Also referred to as "*apparent coefficient of friction*~~*Brake effectiveness*~~" for disc brakes and as *"(internal) brake factor"* for drum brakes.

C* Average by distance brake effectiveness for drum brakes (internal brake factor)

3.1.25~~6~~. "*Average by distance*" means the averaging method for a given measurand during a brake deceleration event where the sampling frequency is a unit of calculated vehicle distance travelled between sampling points. The resultant value yields the same result as the integration between two instances (start and end thresholds ~~and end of level reached~~) divided by the distance travelled (or driven) during the corresponding elapsed ~~this~~ time ~~lapse~~. During dynamometer testing, the integration of distance is calculated using the difference in brake speed and the elapsed time.

ILS3: CONCLUDING REMARKS

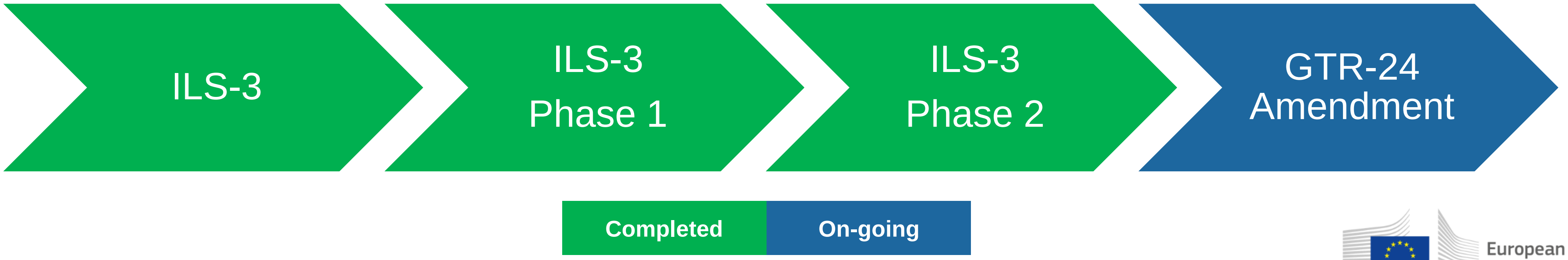
- ✓ Quality of reports and results improved in Phase 2 compared to Phase 1
- ✓ For ILS3, issues still observed for almost every lab (lack of testing experience, incomplete data, inconsistent reporting, etc.)
- ✓ Standard deviation of PM measurements are comparable in terms of absolute value for PUMA and JLR (approx. 0.5 mg/km/brake)
- ✓ Due to lower PM emission level, CoV appears 3 times higher for low emitting brakes (approx. 9% for PUMA vs. approx. 28% for JLR)
- ✓ Background PN-level indicated very good background emission control in GTR 24 compliant setups

ILS3: CONCLUDING REMARKS [contd.]

- ✓ Influence of volume flow on brake temperatures is negligible
- ✓ Influence of volume flow on emission level cannot be clearly identified
  - Brake emissions behaviour was not stabilized to a lower variation
  - Different EFs between samples M1 & M2
- ✓ PN background is 1-2 orders of magnitude less than the PN Efs
- ✓ Brake threshold pressure proposed for disc brakes
- ✓ Revision of friction work method proposed
- ✓ New definitions added for deceleration *actual* start & end times

ILS3 OBJECTIVES & APPROACH

- ✓ Examine the repeatability and reproducibility of PM and PN emission measurements with the application of the GTR-24 protocol; **PARTIALLY COMPLETED**
- ✓ Understand the capability of participating labs to carry out brake PM and PN emission measurements in accordance with the GTR-24 – Help the laboratories to finetune their setup and improve their processes; **COMPLETED**
- ✓ Provide recommendations to the PMP on further improving and finetuning the defined specifications in the GTR-24; **COMPLETED**



ILS3: NEXT STEPS

- ✓ Effects of brake torque behavior on specific KE, EFs, and wear
- ✓ If deemed essential, identify torque quality metrics
- ✓ PN-to-PM correlations
- ✓ PM-to-wear correlations
- ✓ Effect of 5 sec addition at the end of each trip on PN results

SPECIAL ACKNOWLEDGEMENTS

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Ford	For support on brake parts and vehicle/brake design details
JLR	For support on brake parts and vehicle/brake design details
Tobias Spannbauer (ZF)	For support on FW method and reference filter weighing clarifications
Tom Gerhard (DRIV)	For identifying corrections in the presented results

And all labs who participated in ILS3 and showed strong commitment from start to end.

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Thank you