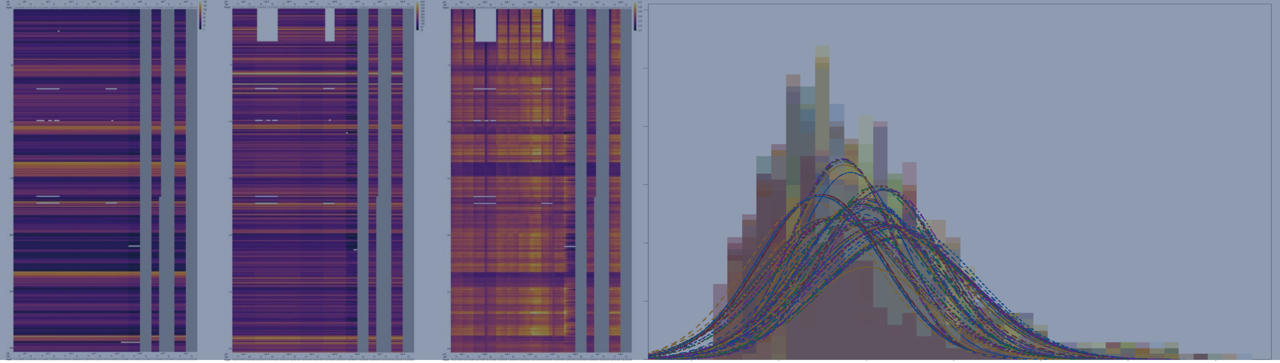


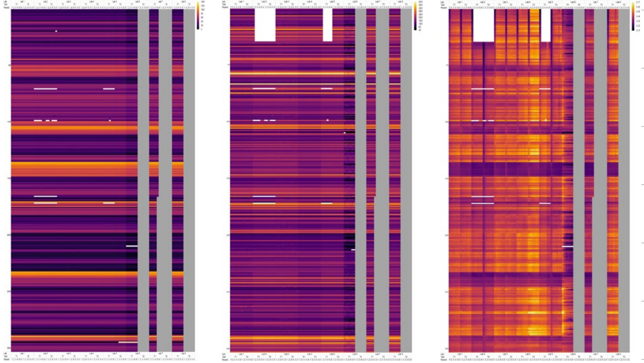
Statistical Evaluation of Euro 7 Laboratory Tests for Brake Emissions Factors

Carlos Agudelo

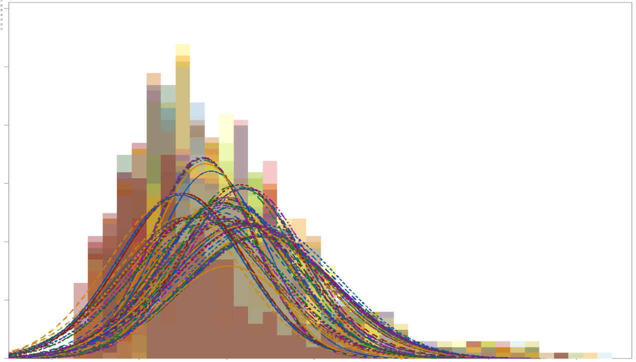
03.14.2024 | CARB Riverside, CA

LINK

OSAR 2024 CONFERENCE
Driving Change for Cleaner Air



Variability components ILS2



Dyno test capabilities

Weighing process capabilities

Sections

Variability components ILS2

- ISO 5725 (2…6)

- repeatability, sample effect, lab effect, total Reproducibility

- s_r, s_H, s_L, s_R
- $CD_{r,}$ CD_R

Acknowledgment

Research members

Carlos Agudelo, Dr. Barouch Giechaskiel, Dr. Theodoros Grigoratos,
Dr. Ing. Jarek Grochowicz, and Dr. Ing. Hartmut Niemann

TF3 members

To **AUDI** AG, **BMW** AG, **Ford-Werke** GmbH, **Stellantis** N.V., **Continental** AG, **DRiV** Inc., **Brembo** S.p.A, and **Volkswagen** AG
For providing brake components

To M. Arndt (**AVL** List GmbH), K. Kolbeck and J. Von-Wild (**BMW AG**), M. Federici (**Brembo** S.p.A.), M. Morbach and C. Kölsch (**DRiV** Inc.), J. Grochowicz (**Ford-Werke** GmbH), G. Kanae Filler and D. Lugovyy (**HORIBA** Europe GmbH), A. Perez and J. Olive (Applus+ **IDIADA**), A. Sin and S. Balestra (**ITT** Inc.), H. Hagino (Japan Automobile Research Institute - **JARI**), R. Vedula and A. Hortet (**LINK**), H. Chong (**NIER**, South Korea), P. Nyhof (**TMD** Friction Services GmbH), H. Niemann and H. Kaminski (**TU DARMSTADT**), D. Hesse and C. Hamatschek (**TU ILMENAU**), and P. Jouy (**UTAC** France)
For their technical support during the ILS2

WHY doing this

background and benefits

Estimates of relative contributions to variability

Euro 7

Assess the ability to meet UN GTR 24 requirements

Detect opportunities to improve UN GTR 24

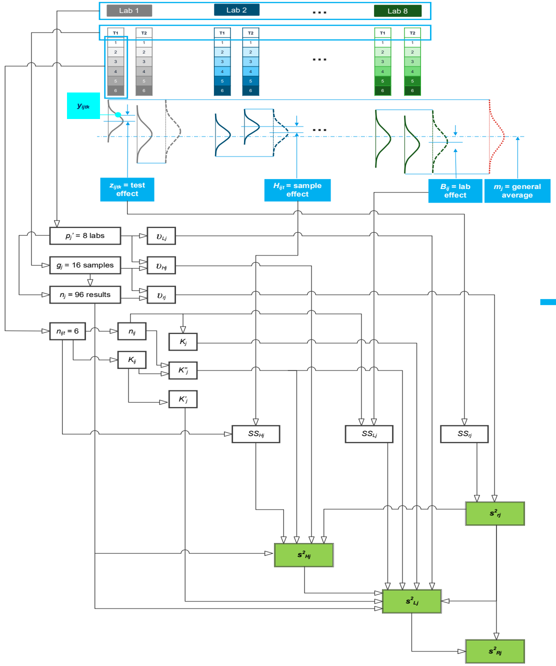
HOW we calculated the standard deviations

ISO 5725-5 for heterogenous materials using non-robust algorithms

Table 1. Main characteristics of tested brakes. WL/DM = Wheel load/Disc mass. ECE refers to European performance brake pads. NAO refers to non-asbestos organic brake pads.

Brake ID	Axle	Vehicle Test Mass [kg]	Vehicle Type [-]	Test Inertia [kg·m^2]	Rolling Radius [mm]	Friction Material	WL/DM Ratio [-]
Br1Fa	Front	1600	M1 (Sedan)	49.3	315	ECE	88.1
Br1Fb	Front	1600	M1 (Sedan)	49.3	315	NAO	88.1
Br2	Front	1668	M1 (Sedan)	50.8	321	ECE	44.6
Br3	Front	2623	M1 (SUV)	112.1	383	ECE	50.7
Br4	Rear	1253	M1 (Compact)	16.1	314	-	44.7
Br5La	Front	2500	N1 (Van)	86.7	345	ECE	90.1
Br5Lb	Front	3390	N1 (Van)	117.6	345	ECE	122.1

Using the same brake as ILS1



ISO 5725-5 for s_r, s_H, s_L, s_R

High-level metrics for entire test

Event-based for measurand results

Statistical report

WHAT we measured

basis to establish critical differences (CD_r for test-to-test and CD_R for dyno-to-dyno) per ISO 5725-1, -6

s_r repeatability (tests)
s_H Sample (friction couple)
s_L Laboratory/Dynamometer

s_R Reproducibility

ISO 5725-5

$$s_R^2 = s_r^2 + s_L^2$$

4.1.4 In view of 4.1.1 to 4.1.3, when examining two single test results obtained under repeatability or reproducibility conditions, the comparison shall be made with the repeatability limit

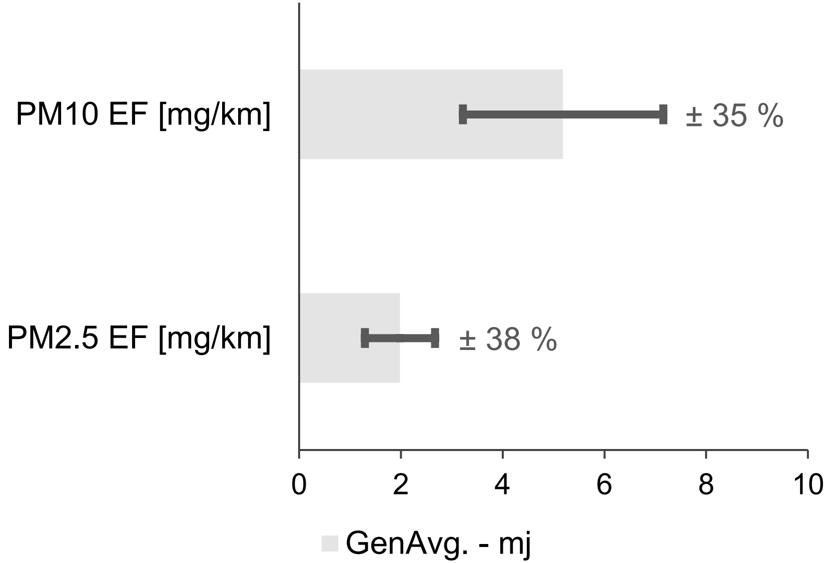
$$r = 2{,}8\sigma_r$$ ...between tests

or the reproducibility limit

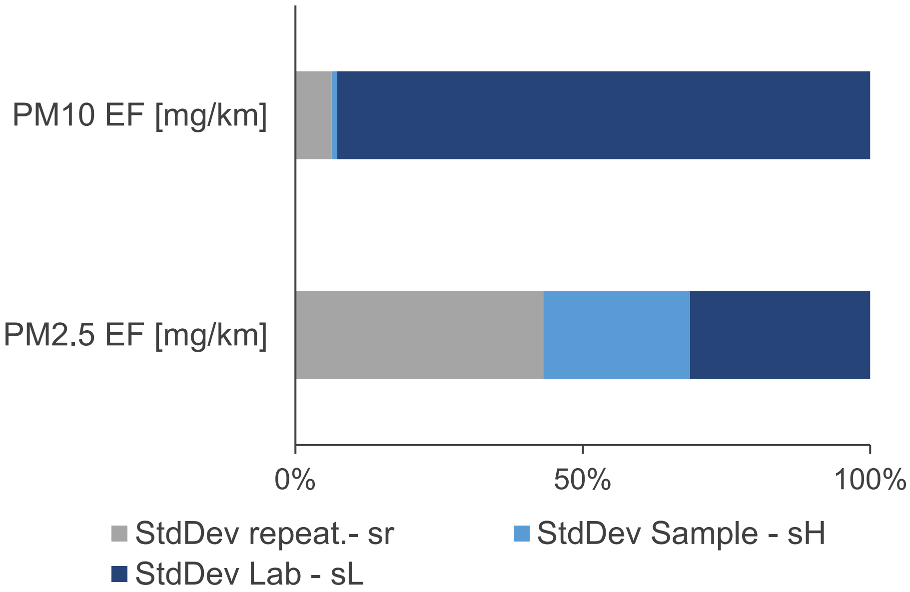
$$R = 2{,}8\sigma_R$$ ...between labs/dynos

STATISTICS for emissions factors

lab is main component for PM_{10} variability, while repeatability is main component for $PM_{2.5}$



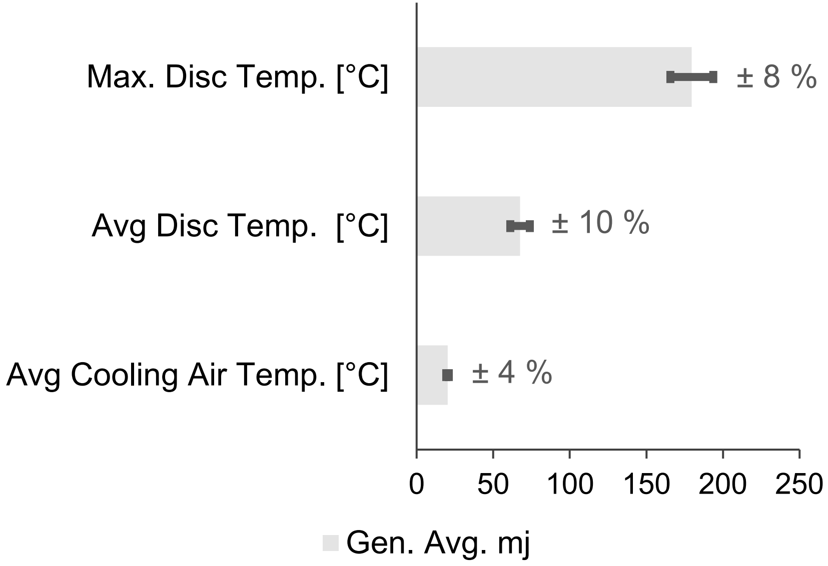
Overall mean and Reproducibility (error bar)



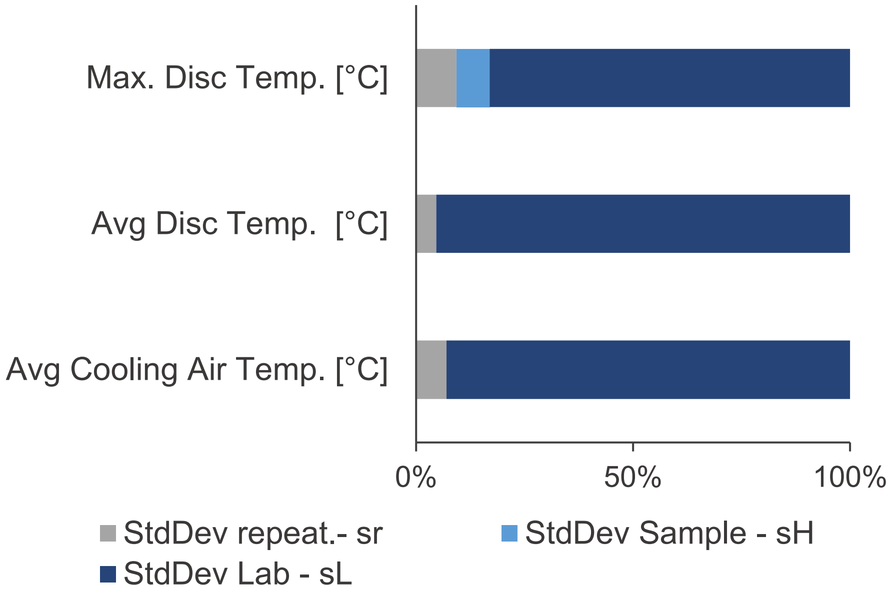
Percent contribution to total variance by component

STATISTICS for overall brake and cooling air temperatures

lab is main contributing factor to variability



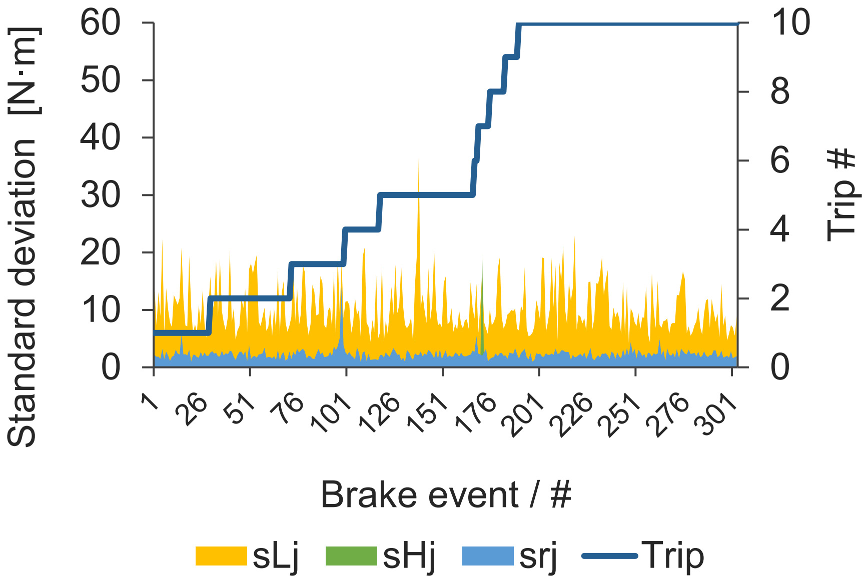
Overall mean and Reproducibility (error bar)



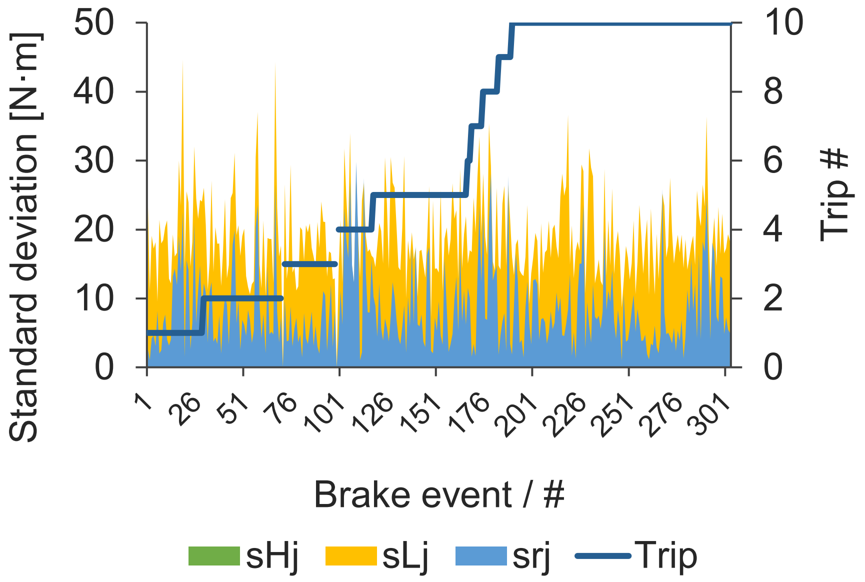
Percent contribution to total variance by component

Components of variability for avg-by-time torque by event

larger scatter for all factors during ILS2



ILS1



ILS2

Sections

Variability components	Dyno test capabilities
• ISO 5725 (2…6)	• ISO 22514 (2…7) • GTR 24
• repeatability, sample effect, lab effect, total Reproducibility	• Bias, repeatability, linearity
• s_r, s_H, s_L, s_R • $CD_{r,}$ CD_R	• U_{MS}, Q_{MP}, P_{pk}

Acknowledgment

Research members

Carlos Agudelo, Dr. Ing. Hartmut Niemann, Maximilian Hense, Alejandro Hortet, James Boatwright, Dr. Frederik Weis

Those working behind the scenes

Barry Purtymun, from LINK-Arizona, for processing the dyno data using the UN GTR 24 test report output

Tyler Odom, from LINK Technical Center-Dearborn, Michigan, for making the UN GTR 24 test report work

HOW to assess the different UN GTR 24 requirements

using three categories of data

Continuous (ISO 22514-7)	Time-based (ISO 22514-2)	Attributes (ISO 22514-5)
Measurands that vary during the test: ▪ Braking / release speed ▪ Deceleration / torque ▪ Event duration ▪ …	Constant measurands during the test: ▪ Cooling airflow ▪ Cooling air temp. and %RH ▪ PM/PN sampling flow ▪	Measurands expressed as Y/N or %: ▪ Speed violations ▪ Kinetic energy dissipation ▪ Test level background compliance ▪ …

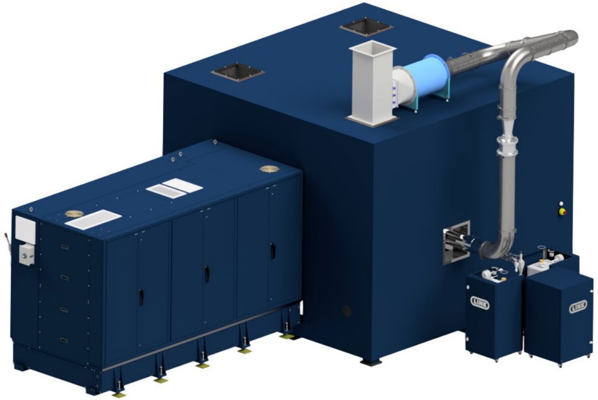
HOW to assess the different UN GTR 24 requirements

using three categories of data

Continuous (ISO 22514-7)	Time-based (ISO 22514-2)
Measurands that vary during the test: ▪ Braking / release speed ▪ Deceleration / torque ▪ Event duration ▪ …	Constant measurands during the test: ▪ Cooling airflow ▪ Cooling air temp. and %RH ▪ PM/PN sampling flow ▪ …

HOW we compiled the data

use of dyno data from two standard configurations + brake emissions upgrade



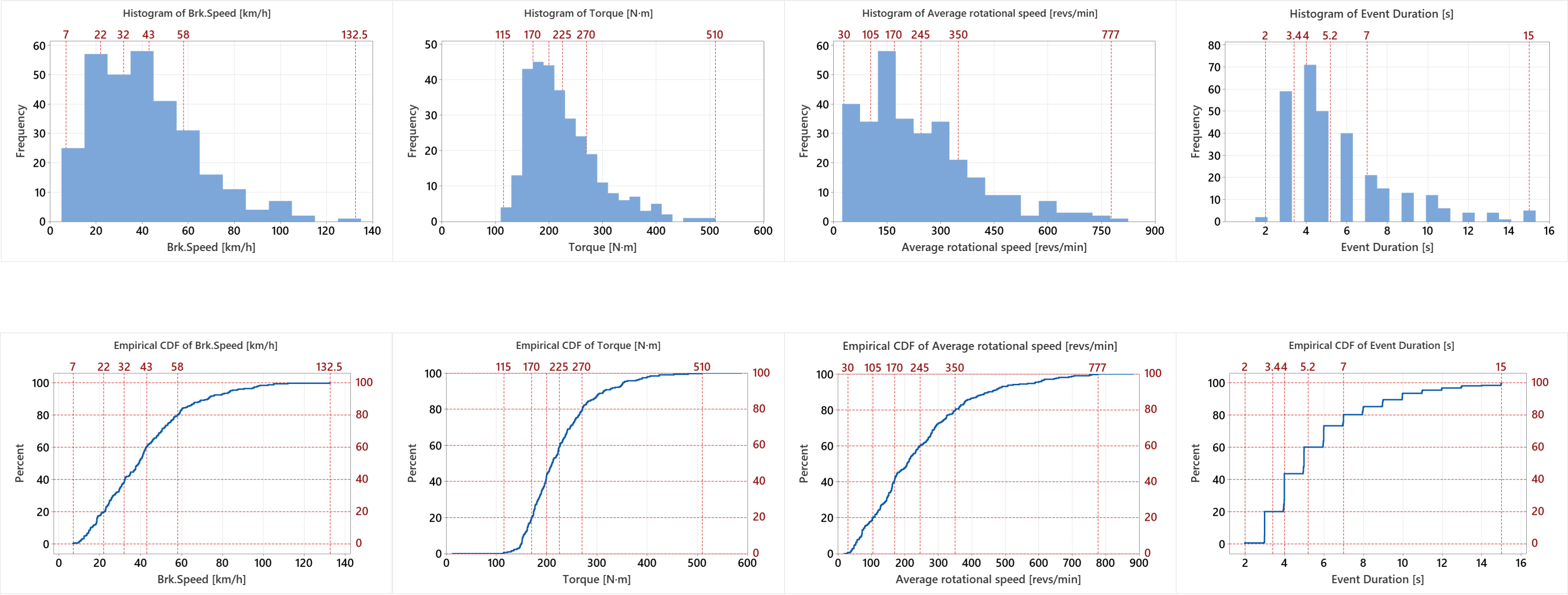
(A) M3000 performance		(B) M3900 NVH	
Motor: 186 kW	FS torque: 5600 N·m	Motor: 186 kW	FS torque: 5600 N·m
Maximum simulated inertia: 260 kg·m²		Maximum simulated inertia: 320 kg·m²	
Maximum speed: 300 km/h @ r_R: 0.4 m		Maximum speed: 375 km/h @ r_R: 0.4 m	
M6330 + M4222 per UN GTR 24		M6330 + M4222 per UN GTR 24	
Test loads: I_t = 80 kg·m²; r_R = 0.340 m		Test loads: I_t = 50 kg·m²; r_R = 0.290 m	
Brake size: r_{eff} = 120 mm; d_{piston} = 60 mm × 1		Brake size: r_{eff} = 108 mm; d_{piston} = 60 mm × 1	

HOW we selected the levels for the one-way ANOVA (ISO 22514-7)

minimum + 20th percentiles + maximum level (3-parameter lognormal distribution)

Histograms of Set Values

Cumulative Density Function



Braking Speed | Avg-by-time Torque | Avg-by-time Rotational Speed | Event Duration

HOW do the statistics work (ISO 22514-7 + VDA Guide 5) for brake work

- using **M**aximum **P**ermissible **E**rrors to estimate the allowable relative uncertainties
- combining torque and revolutions to stop (uncorrelated components per GUM)
- expressed as relative uncertainties (%)

$$\frac{MPE_{KE}}{\sqrt{3}} = \sqrt{\frac{MPE^2_{AVG-TORQUE}}{3} + \frac{MPE^2_{AVG-REVS}}{3}} \longleftrightarrow u_{KE} = \sqrt{u^2_{AVG-TORQUE} + U^2_{AVG-REVS}}$$

$\downarrow$

$MPE_{KE} \leq 5\%$ per UN GTR 24

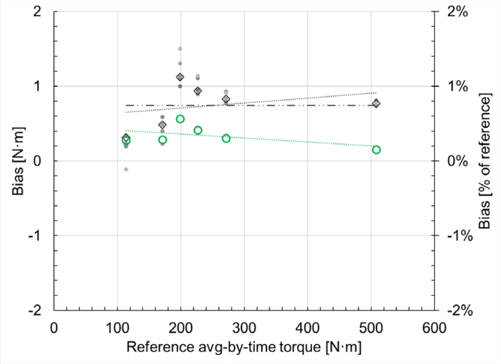
$\downarrow$

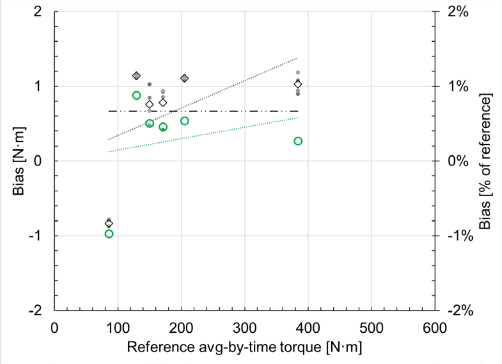
$$\frac{5\%}{\sqrt{3}} = \sqrt{\frac{3.54\%^2_{AVG-TORQUE}}{3} + \frac{3.54\%^2_{AVG-REVS}}{3}} \longleftrightarrow 2.887\%_{KE} = \sqrt{2\%^2_{AVG-TORQUE} + 2\%^2_{AVG-REVS}}$$

WHAT we calculated for average-by-time torque

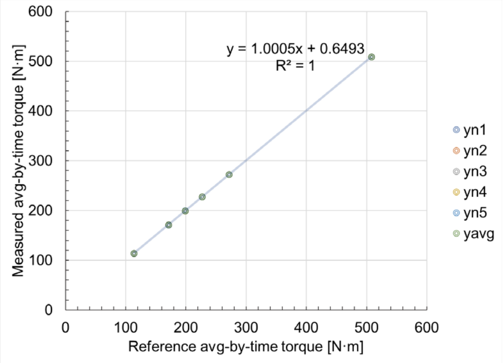
correlation of test averages with reference values, bias, and components of uncertainty

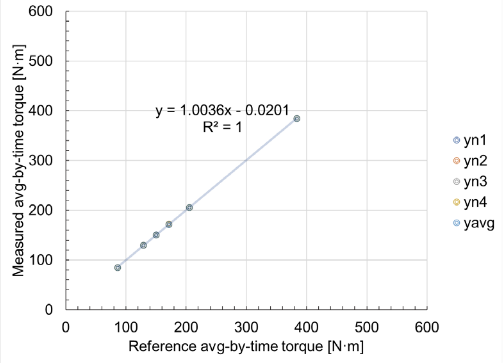
Bias (value and %)





Linearity





Dyno (A) Dyno (B)

Metrics for uncertainty		Dyno (A)	Dyno (B)
BIAS [N·m]	u_{BI}	0.428 6	0.382 8
LINEARITY [N·m]	u_{LIN}	0.261 4	0.751 4
REPEATABILITY [N·m]	u_{EVR}	0.100 2	0.151 1
Combined uncertainty [N·m]	u_{MS}	0.512 0	0.856 7
Combined exp. uncertainty [N·m]	U_{MS}	1.024 0	1.807 6
COMBINED EXPANDED UNCERTAINTY	—	**0.41%**	**0.96%**
Performance ratio ($\leq$ 30%)	Q_{MP}	8.2%	19.2%

HOW do the statistics work (ISO 22514-7)

- using ANOVA to estimate the actual relative uncertainties
- combining torque and revolutions to stop (uncorrelated components per GUM)
- expressed as relative uncertainties (%)

$$u_{KE} = \sqrt{u^2_{AVG-TORQUE} + u^2_{AVG-REVS}}$$

$$\downarrow$$

$$u_{KE} = \sqrt{0.00335^2 + 0.0066^2} = 0.74\ \% \ \leq \ \{5\ \%/\sqrt{3} = 2.887\ \%\}$$

$$\downarrow$$

$$Q_{MP_{KE}} = 2 \times U_{KE}/(U - L) = 2 \times 1.5\ \%/10\ \% = 30\ \%\ \text{(performance ratio)}$$

HOW to assess the different UN GTR 24 requirements

using three categories of data

Continuous (ISO 22514-7)	Time-based (ISO 22514-2)
Measurands that vary during the test: ▪ Braking / release speed ▪ Deceleration / torque ▪ Event duration ▪ …	Constant measurands during the test: ▪ Cooling airflow ▪ Cooling air temp. and %RH ▪ PM/PN sampling flow ▪ …

HOW we assessed time-based data (ISO 22514-2)

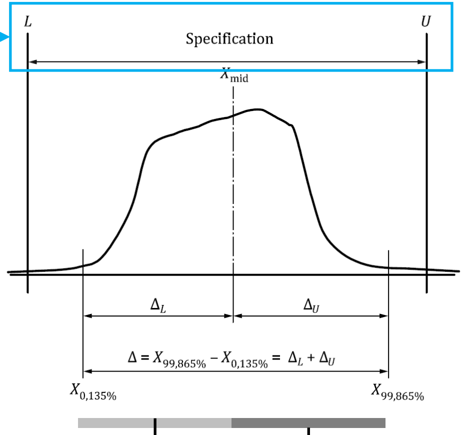
high-level workflow for performance metrics (before confirming process is under statistical control)

Table 7.2.
Summary of cooling air temperature, humidity, and flow requirements

Parameter	*Cooling air temperature*	*Cooling air relative humidity*	*Cooling airflow*
Nominal value	23 °C	50 %	Set value (Q_{set}) per paragraph 10.
Average value: Maximum permissible tolerance	±2 °C	±5 %	±5 % of Q_{set}
Instantaneous values (1Hz): Maximum permissible tolerance	±5 °C	±30 %	±5 % of Q_{set}
Instantaneous values (1Hz): Permissible deviation beyond the maximum permissible tolerance	Not defined	Not defined	±10 % of Q_{set}
Instantaneous values (1Hz): Maximum time exceeding the maximum permissible tolerance	10 % of each test section's duration	10 % of each test section's duration	5 % of each test section's duration

PM sampling flow — 12.1.2.3.(d) The average sampling volumetric flow shall be within ± 2 per cent of the set value […]

PN sampling flow — 12.2.3.2. (c) The actual normalised sampling flow shall not deviate more than ±10 per cent of the average value […]



$$P_{pk_L} = \frac{X_{mid} - L}{\Delta_L} \qquad P_{pk_U} = \frac{U - X_{mid}}{\Delta_U}$$

$$P_{pk} = min\left(P_{pk_L}, P_{pk_U}\right)$$

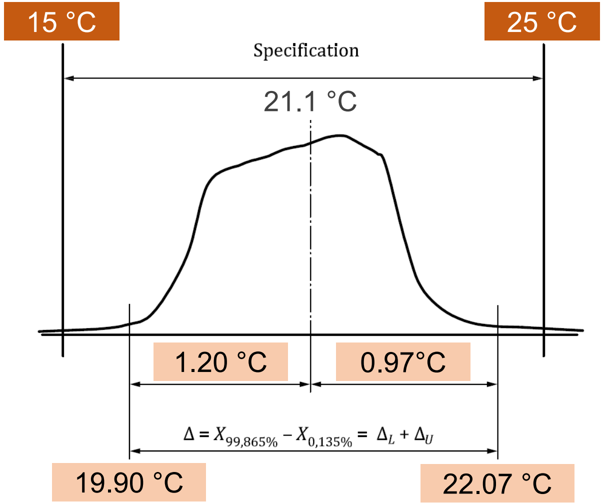
WHAT was the compliance for cooling airflow conditions

using test-specific set values and UN GTR 24 tolerances on Table 7.2

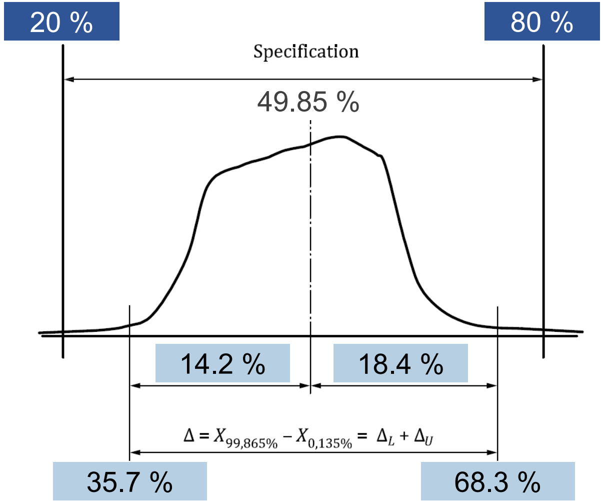
Parameter	*Cooling air temperature*	*Cooling air relative humidity*	*Cooling airflow*
Nominal value	20 ºC	50 %	200 m³/h
Average value: Maximum permissible tolerance	– 1.07 ºC **(± 2 ºC)**	– 0.11 % **(± 5%)**	– 0.4 % **(± 5%)**
Instantaneous values (1Hz): Maximum permissible tolerance	± 5 ºC	± 30 %	± 5 % of Q_{set}
Instantaneous values (1Hz): Permissible deviation beyond the maximum permissible tolerance	Not defined	Not defined	±10 % of Q_{set}
Instantaneous values (1Hz): Maximum time exceeding the maximum permissible tolerance	0 % **(± 10%)**	0 % **(± 10%)**	0.0385% **(± 5%)**

WHAT was the performance for cooling airflow conditions

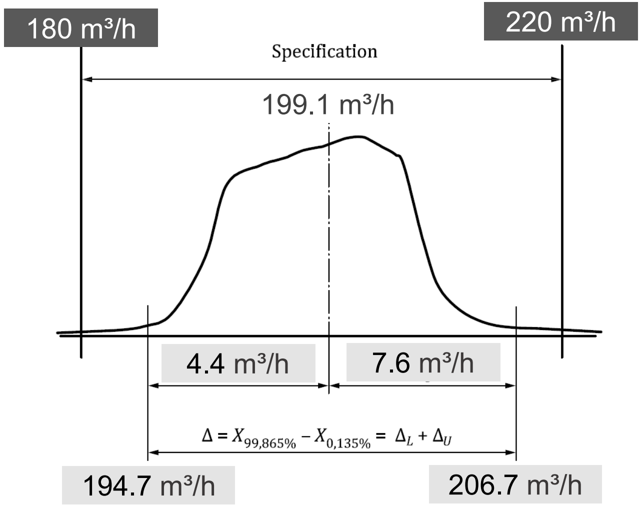
using test-specific set values and ISO 22514-2 indexes



Cooling air temperature (20 °C)
UN GTR 24 bias = – 1.1 °C
P_{pk} = 4.04 > 1.33



Cooling air relative humidity (50 %RH)
UN GTR 24 bias = – 0.11 %RH
P_{pk} = 1.64 > 1.33



Cooling airflow (200 m³/h)
UN GTR 24 bias = – 0.4%
P_{pk} = 2.74 > 1.33

Sections

Variability components	Dyno test capabilities	Weighing process capabilities
• ISO 5725 (2…6)	• ISO 22514 (2…7) • GTR 24	• ISO 22514 (2…7) • GTR 24 • DIN EN 12341
• repeatability, sample effect, lab effect, total Reproducibility	• Bias, repeatability, linearity	• Filter (integrity, charge, stability) • Room (repeatability, conditions) • Sampler (bias, repeatability, linearity, correlation)
• s_r, s_H, s_L, s_R • $CD_{r,}$ CD_R	• U_{MS}, $Q_{MP,}$ P_{pk}	• P_{pk}

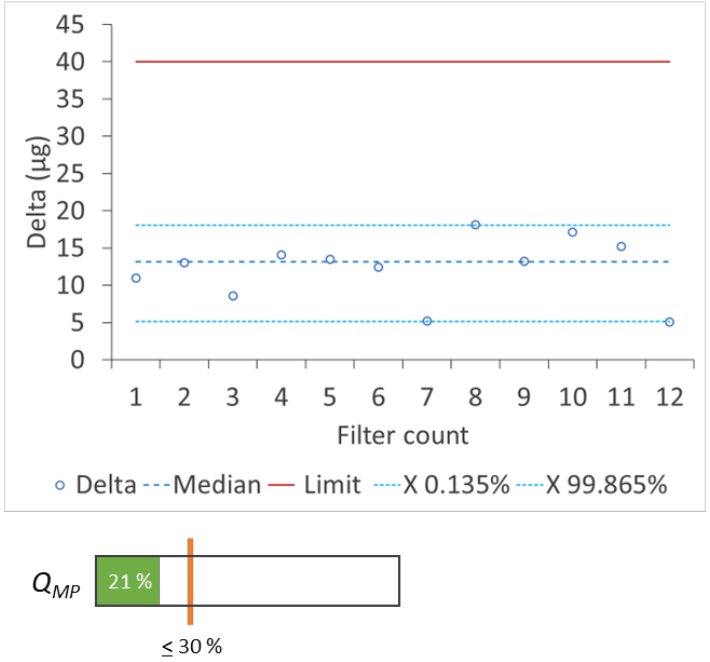
GTR 24 — Weighing room and weighing process requirements (extract)

Including microbalance, room, filter conditioning, and variability

Room	Microbalance	Process
• Free of contaminants • (22 ± 2)°C & (45 ± 8) %RH • Filter storage (pre & post) • Buoyancy correction	• Isolation from vibration • Calibration report • Calibrated weights • Resolution ≤ 1 µg	• ± 10 µg reference filters • $\lvert m_1 - m_2 \rvert \leq 10$ µg or range $\lvert m_1 \ldots m_4 \rvert \leq 15$ µg

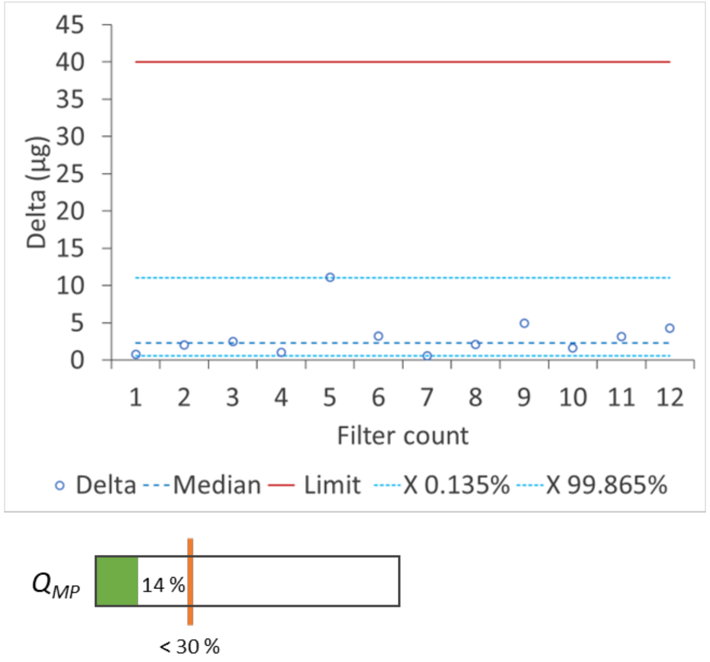
DIN EN 12341 — C.2. Filter integrity

condition & weigh → holder
→ wait 1 hour → remove weigh



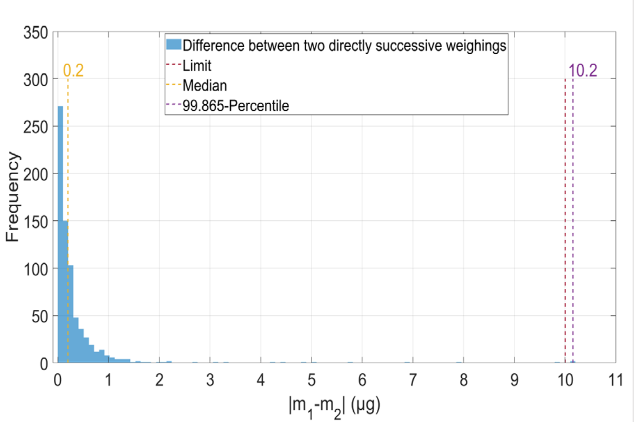
DIN EN 12341 — C.2. Static charge

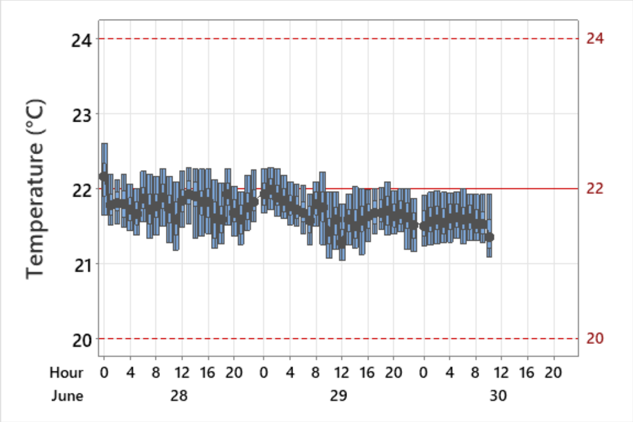
condition & weigh (without discharge)
→ static discharge → reweigh

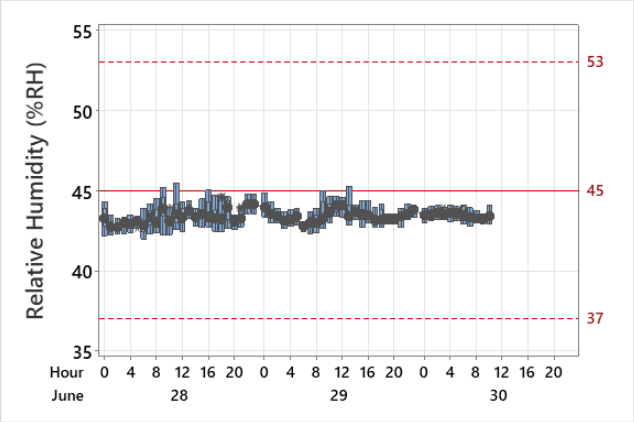


DIN EN 12341 — D.1. Accuracy and stability of room conditions

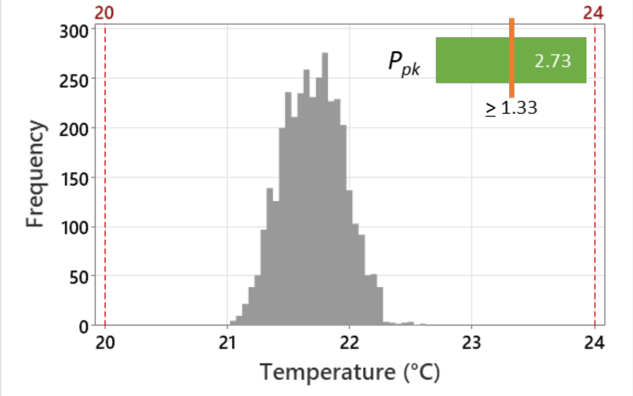
$\lvert m_1 - m_2 \rvert \leq 10$ µg	20 °C ≤ RT ≤ 24 °C	37% ≤ RT ≤ 53%

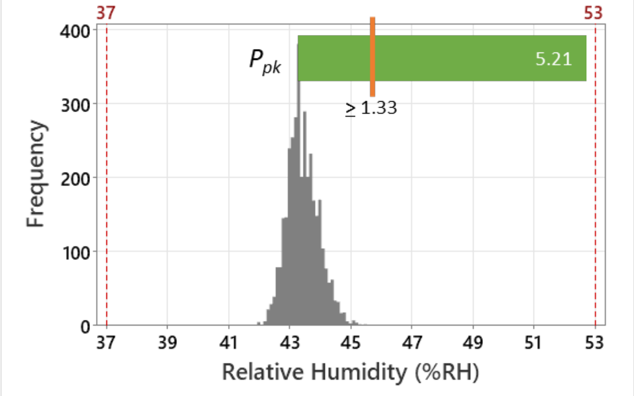






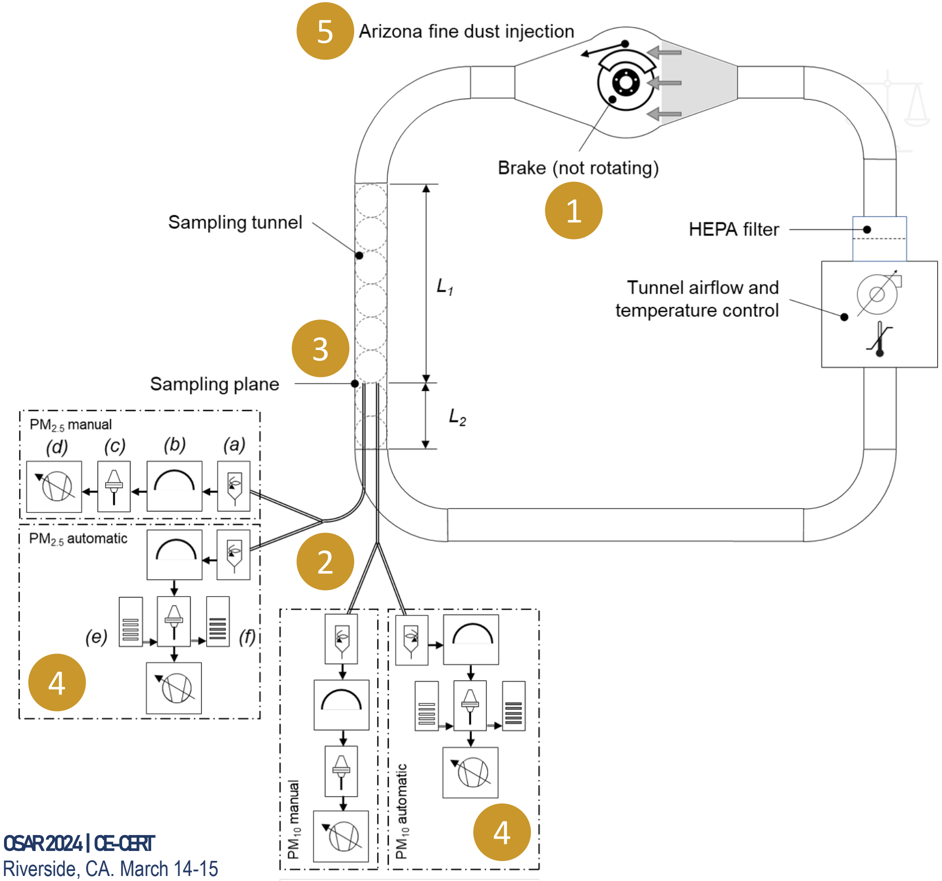
> 700 tests routine tests





Experimental setup for level and detection and Two-Way ANOVA

Gtr 24-modified to accommodate measurements close to DIN EN 12341

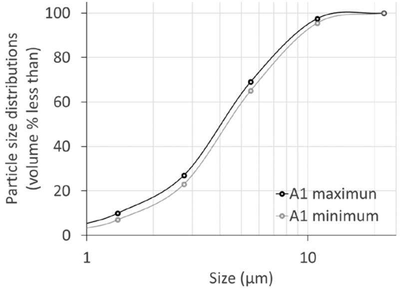


1. Non-rotating brake
2. 20° balanced flow splitters
3. 0.95…0.98 isokinetic ratio @ 33.3 lpm
4. Manual and automatic filter changers
5. PALAS RBG Basic dust generator

Experimental setup for level and detection and two-way ANOVA

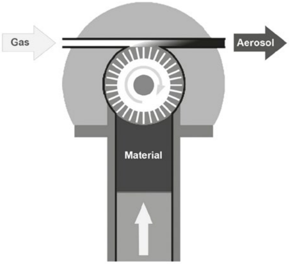
PALAS adjustable generator to inject ISO 12103-1 Arizona fine dust

AZ fine dust



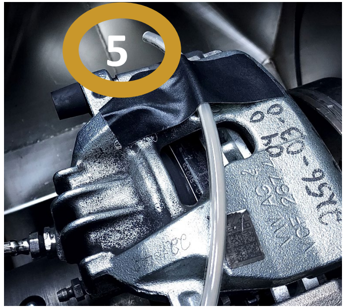
AZ fine dust size distribution

AZ fine dust cylinders



RBG working principle

RBG industrial embodiment

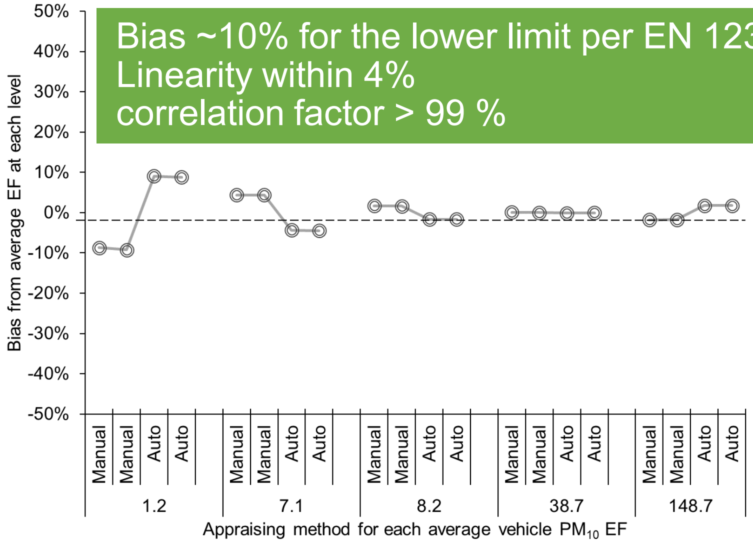


Injection at brake enclosure

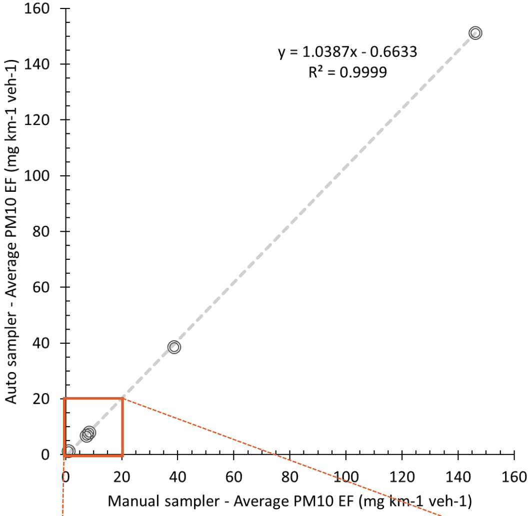
ISO 22514-7 between samplers ANOVA

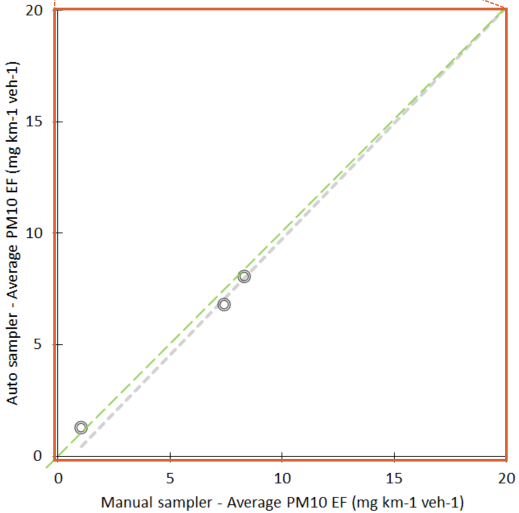
Two sampling systems (manual and auto) and five filter load levels

Test case	PM_{10} EF ($mg\ km^{-1}\ veh^{-1}$)	Estimated filter load (mg)
EN 12341 lower limit (~1 µg m^{-3})	1.2	0.070 3
Euro 7 target	7.1	0.432 6
Euro 7 target + 20%	8.2	0.496 7
Five times Euro 7 target	38.7	2.351 8
EN 12341 upper limit (~150 µg m^{-3})	148.7	9.035 4

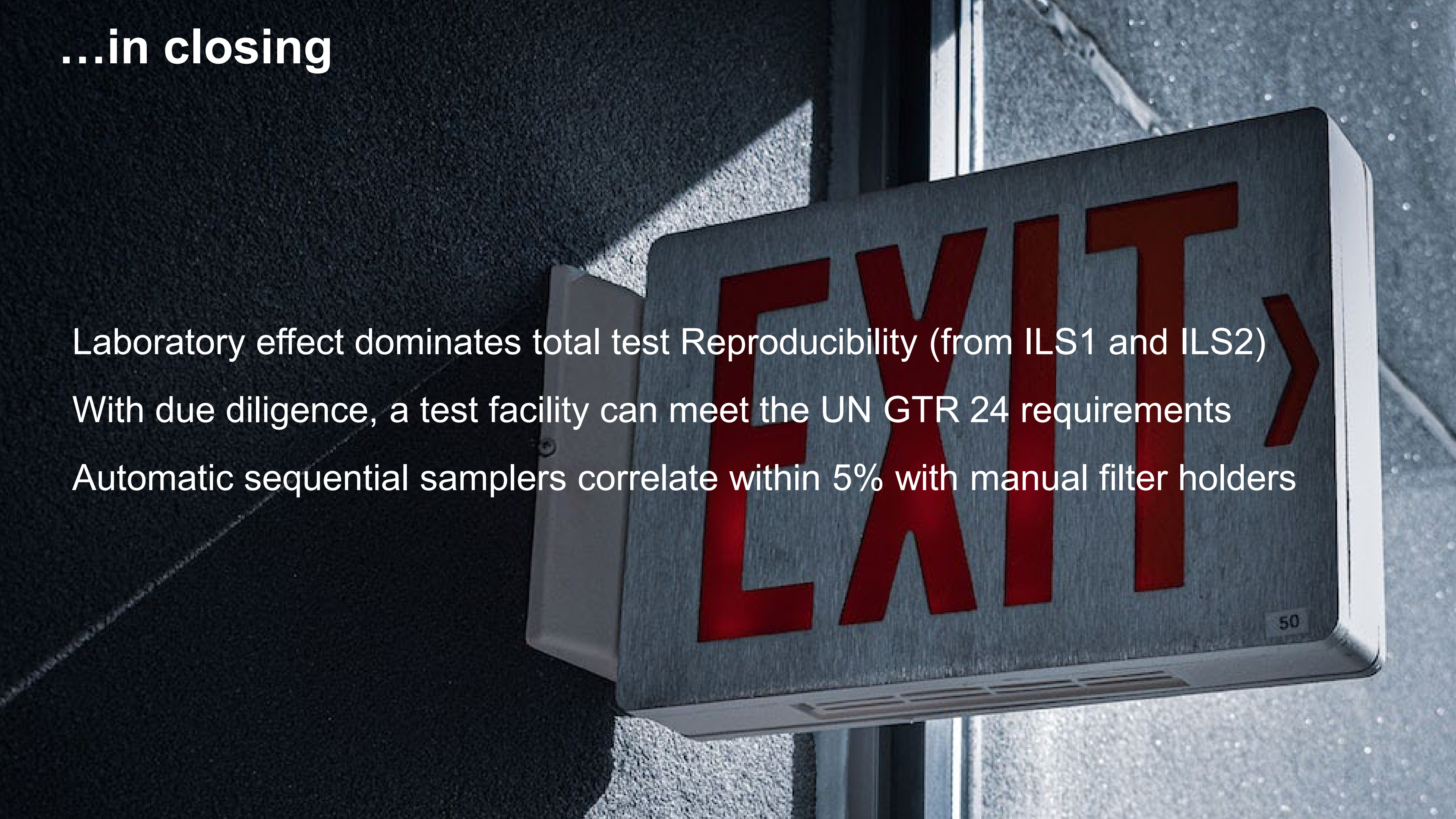


Bias ~10% for the lower limit per EN 12341
Linearity within 4%
correlation factor > 99 %





…in closing



Laboratory effect dominates total test Reproducibility (from ILS1 and ILS2)

With due diligence, a test facility can meet the UN GTR 24 requirements

Automatic sequential samplers correlate within 5% with manual filter holders

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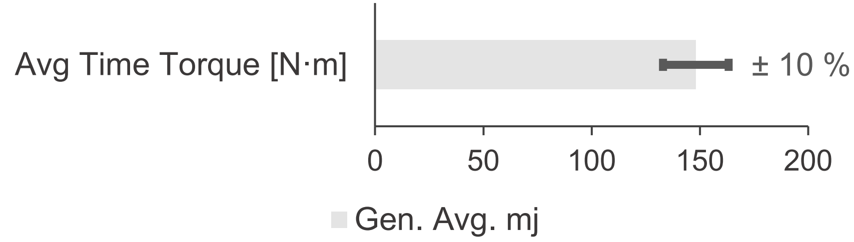
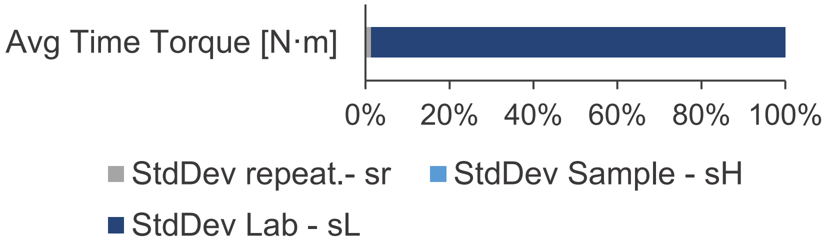
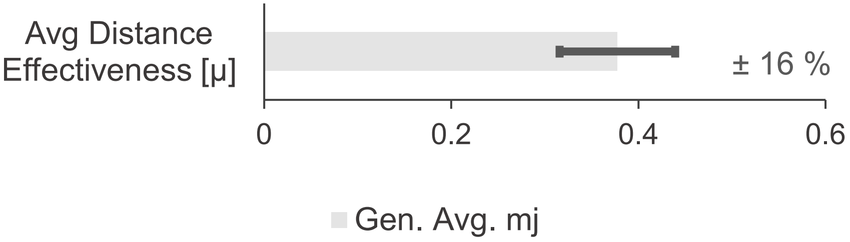
LINK

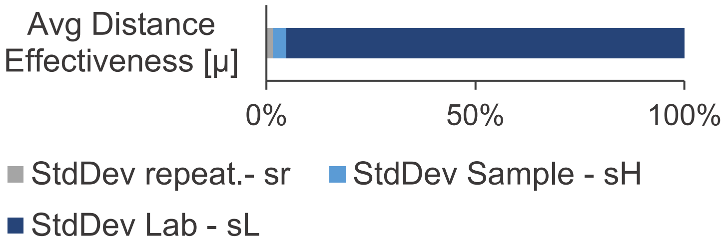
STATISTICS for brake torque and coefficient of friction

both dominated by lab effect









Overall mean and Reproducibility (error bar)

Percent contribution to total variance by component

Summary on test variability

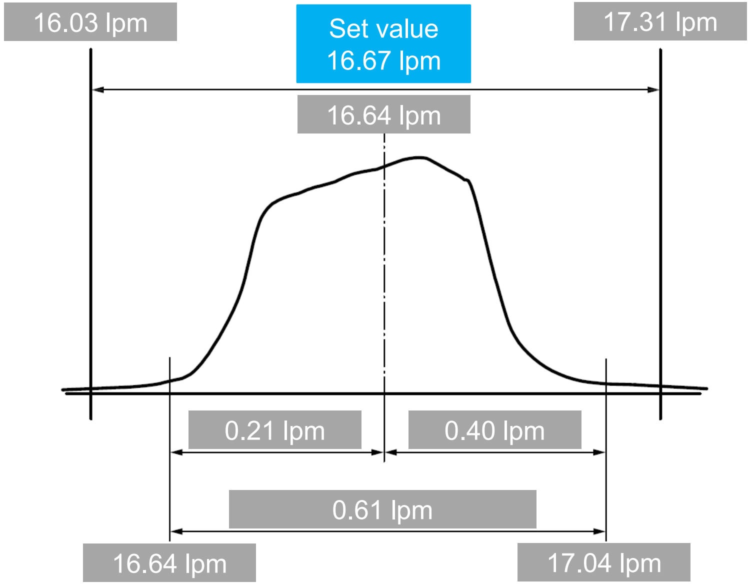
- for brake work and brake temperature, lab variability is key
- ILS3 needs to (and it is) including test repeats to ensure proper statistics

Average-by-Time Torque

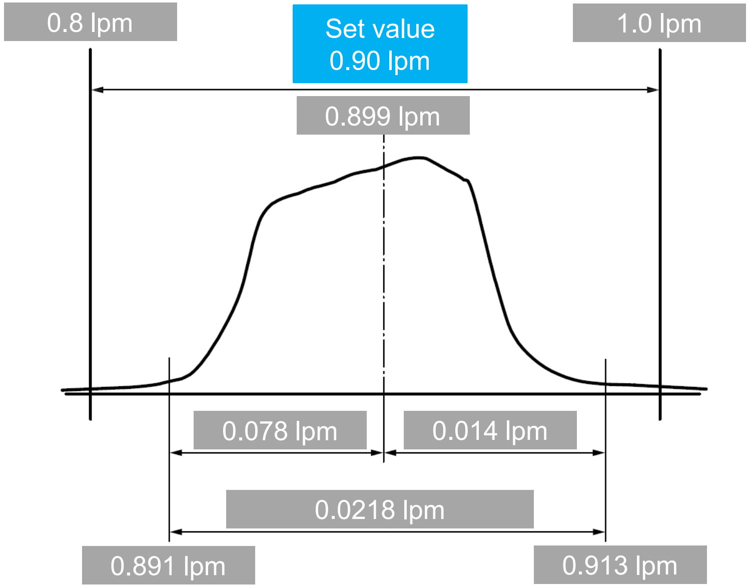
Events	ILS1				ILS2			
	Standard deviations (repeat., Sample, Lab, Reproducibility) as percent of the general average							
	s_{rj}	s_{Hj}	s_{Lj}	s_{Rj}	s_{rj}	s_{Hj}	s_{Lj}	s_{Rj}
303	1.4%	0.1%	6.1%	6.3%	5.7%	0.0%	12.9%	14.3%
50th	1.3%	0.0%	5.4%	5.5%	4.7%	0.0%	12.3%	13.5%
95th	2.0%	0.5%	11.2%	11.3%	14.2%	0.0%	20.6%	25.0%

WHAT was the performance for PM_{10} and TPN sampling airflows

using test-specific values and ISO 22514-2 indexes



PM_{10} sampling (16.33…17.00 lpm)
UN GTR 24 bias = 0.02%
P_{pk} = 1.66 > 1.33



TPN sampling (0.81…0.99 lpm)
UN GTR 24 bias = 0.001%
P_{pk} = 7.3 > 1.33