Brake Emission PM Repeatability Assessment

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Content

Assess PM EF measurement chain with respect to repeatability
and
identify potential to improve robustness of the test procedure

Definition of PM EF in the current text

The calculation formula summarizes the influencing factors

Gauss' error propagation law allows to pinpoint most important parameters based on text definitions

Process & laboratory proficiency parameters

PM filter masses observed during operative testing

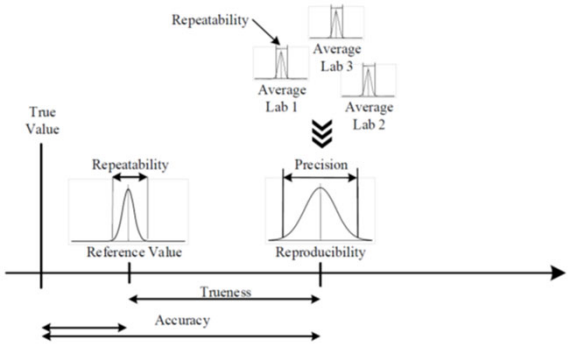
Repeatability of filter weighing and influence of filter handling on filter weight

Summary

Realistically, repeatability can be much better

Takeaways

Terms and Definitions



- Measurement repeatability:
  Measurement precision under a set of repeatability conditions of measurement
- Measurement reproducibility:
  Measurement precision under reproducibility conditions of measurement
- Measurement precision:
  Closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions
- Repeatability condition of measurement:
  Condition of measurement, out of a set of conditions that includes the same measurement procedure, same operators, **same measuring system**, **same operating conditions** and same location, and **replicate measurements on the same or similar objects** over a short period of time
- Reproducibility condition of measurement:
  condition of measurement, out of a set of conditions that includes **different** locations, operators, **measuring systems**, and replicate measurements on the same or similar objects

Differences in system setup influence mainly reproducibility between testbeds due to e. g. inherent losses.

Repeatability focuses mainly on operative proficiency and is an absolute prerequisite for reproducibility.

Source: BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP, and IML. International vocabulary of metrology - Basic and general concepts and associated terms (VIM). Joint Committee for Guides in Metrology, JCGM 200:2012. (3rd edition).

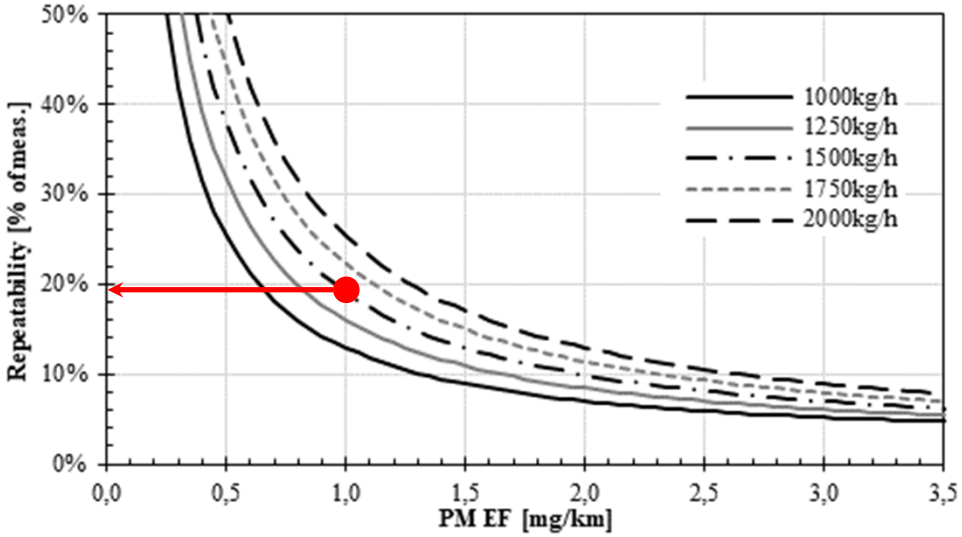
PM Emission Factor Basic Calculation

$$PM\ EF = \frac{m_{Filter} \cdot \frac{m_{Total}}{m_{Sample}}}{d}$$

$$m_{Filter} = m_{Filter,loaded} - m_{Filter,empty}$$

$PM\ EF$	Emission Factor in mg/km
m_{Filter}	Filter loading in mg (mass difference between empty and loaded filter)
$m_{Filter,loaded}$	Filter mass of loaded filter in mg
$m_{Filter,empty}$	Filter mass of empty filter in mg
m_{Total}	Total mass of cooling air flowing through the enclosure during PM sampling in kg
m_{Sample}	Mass sampled through filter during PM sampling in kg
d	Distance driven during PM sampling (= total distance) in km

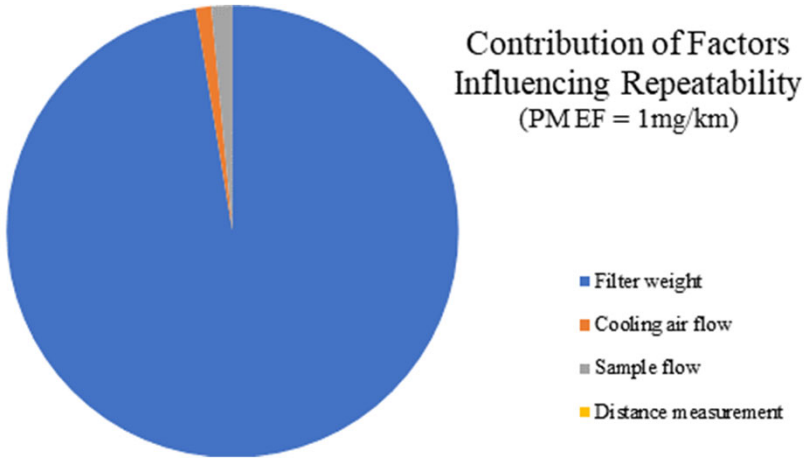
GTR Minimum Requirements
Repeatability to be Expected and Important Contributors



- Calculated using Gauss' error propagation law
- Based on GTR minimum accuracy requirements for the devices used

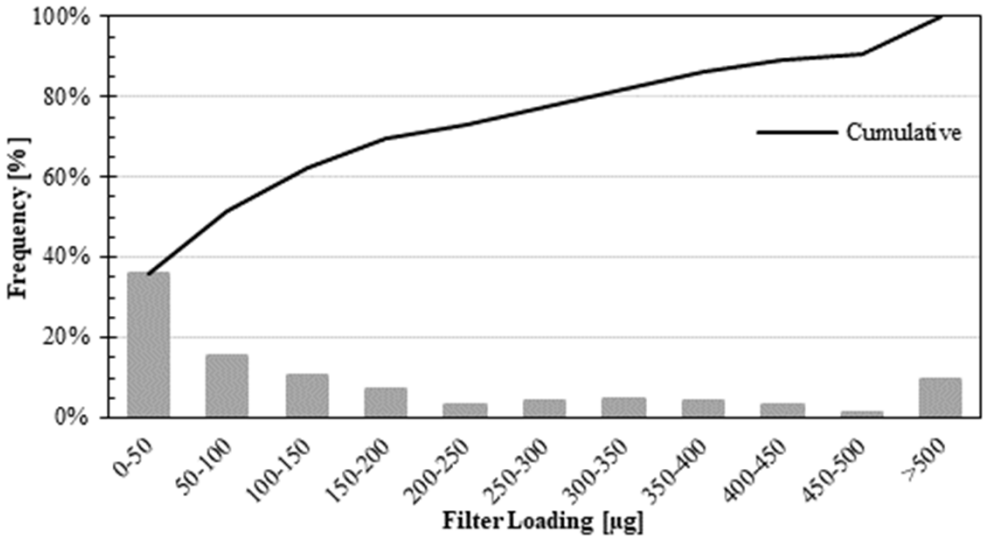
➢ For a PM EF of 1mg/km → r ≈ 20%

➢ PM filter loading is the predominant factor



95% Confidence level, no leaks.
Conditions: WLTP-Brake, Cooling Airflow ±2% accuracy, PM sample flow MPE 2,5% of reading or 1,5% FS, PM weighing repeatability 30µg, 16l/min PM sample flow.

PM Filter Loading
Observed Loadings during operative Testing



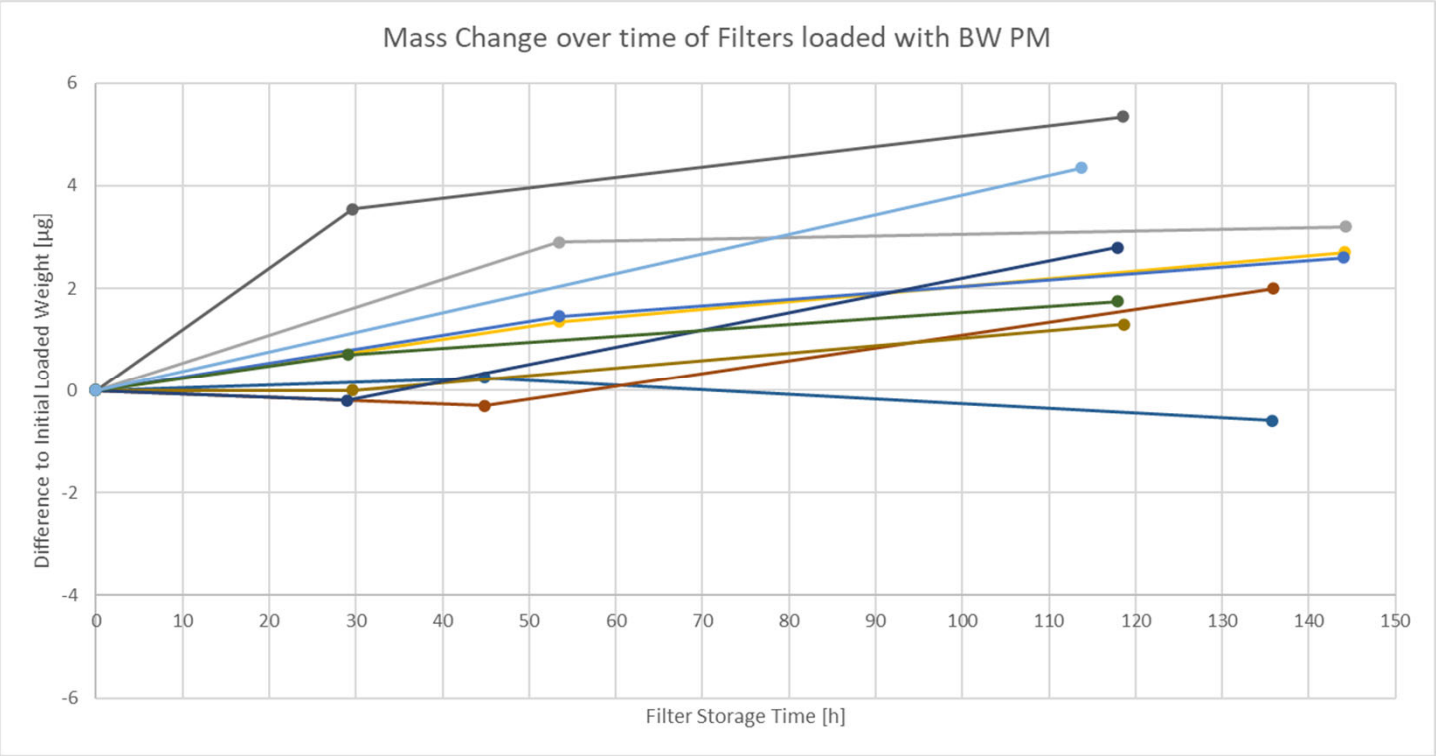
- Basis:
  Nearly 500 filters out of operative testing
  WLTP Brake cycle, several different car sizes
  Different makes and models of brakes
  8 l/min PM sample flow

➢ 50% of observed PM filter loads are below 100µg

- Note:
  The few very heavy filters were typically used for experiments involving more than a single WLTP Brake cycle.

Source: Weidinger Chr., Martikainen S., Wanek-Rüdiger, Chr., et al.: Brake Emission Testing Process – Assuring Repeatability and Reproducibility of Emission Measurement Results. SAE 2023-01-1876. Society of Automotive Engineers, 2023.

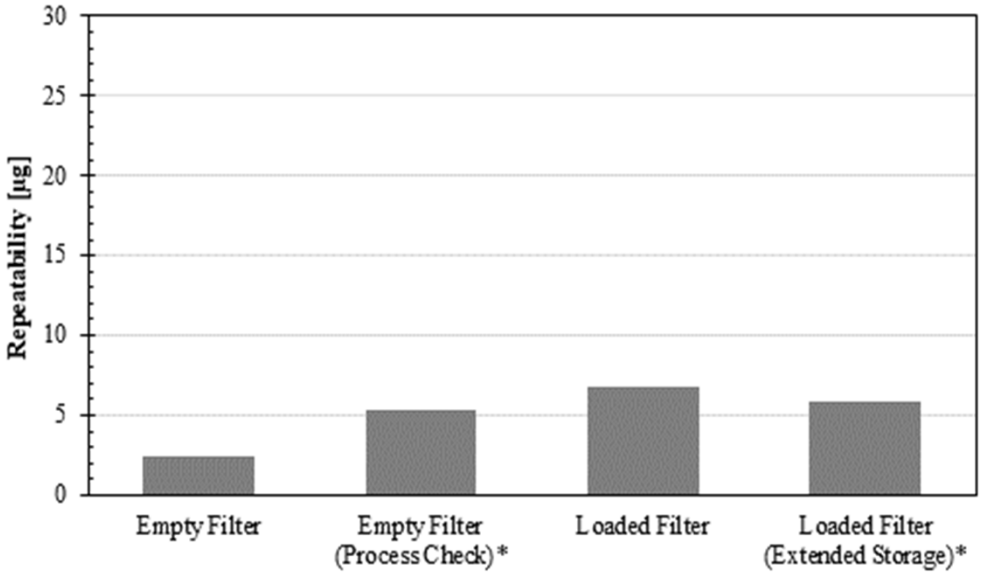
PM Filter Loading
Mass Stability of Loaded Filters over Time



- TX-40 filters loaded with BW PM (ECE pads)
- Initial weighing right after filter loading according to GTR procedure
- After each weighing the filters were transferred back to the testbed and stored there in Petri dishes (uncontrolled environment) for several days
- The results also include the uncertainties caused by transporting the filters back and forth between lab and dyno

- The influence of the time between end of sampling and actual weighing lies within the repeatability of weighing loaded filters – even when stored in an uncontrolled environment and therefore seen uncritical.
- The 8h requirement can be relaxed to more than 48h without deteriorating the results.

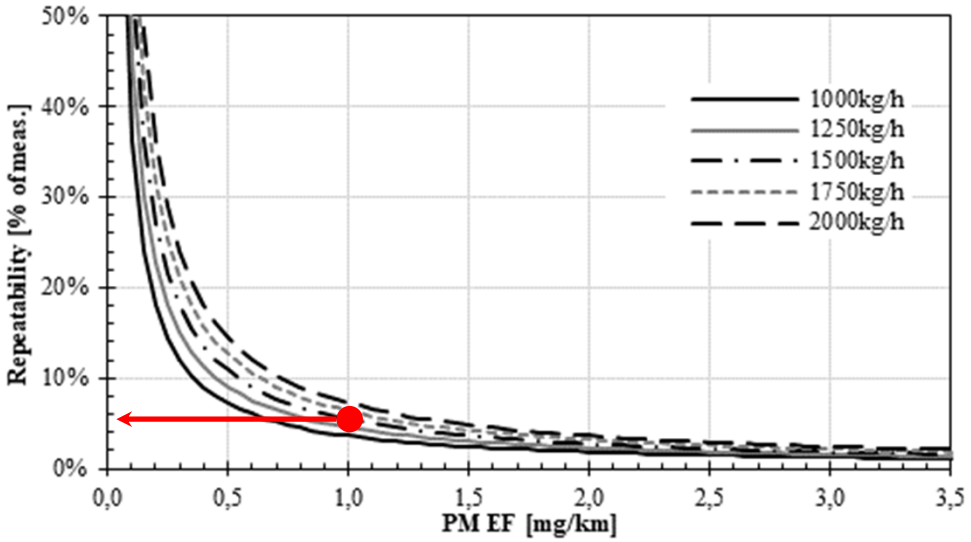
PM Filter Weights
Repeatability of Weighing



- Empty filter: The empty filter is weighed twice as per GTR requirement. The empty filter weight used in the calculations is the average of both. The repeatability statistics is calculated using these two. Individual values on previous slide.
- Loaded filter – Repeatability between the two readings for the loaded filter
- Empty Filter – Process Check:
  Influence of a typical filter handling process – Determine empty filter weight → Put filter into PM Sampler → Remove it form the PM Sampler → Reweight → Calculate filter loading
- Extended Storage → >48h in closed petri dish in the testbed (uncontrolled environment = worst case)

95% Confidence level (2σ), ~500 filters, * ~20 filters
Source: Weidinger Chr., Martikainen S., Wanek-Rüdiger, Chr., et al.: Brake Emission Testing Process – Assuring Repeatability and Reproducibility of Emission Measurement Results. SAE 2023-01-1876. Society of Automotive Engineers, 2023.

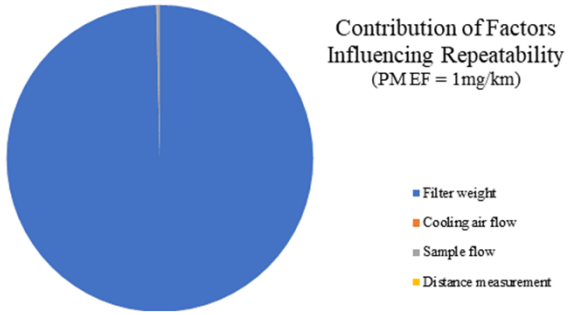
Effect of Stringent Requirements
Repeatability to be Expected and Important Contributors



- Calculated using Gauss' error propagation law
- Based on current AVL standard testbed configuration and laboratory proficiency

➢ Assuming an PM EF of 1mg/km → r ≈ 5%

➢ PM Filter weight remains still the predominant factor



95% Confidence level, no leaks
Conditions: WLTP-Brake, actual testbed configuration (AVL Flowsonix, AVL PM Sampler, current AVL laboratory proficiency), 16l/min PM sample flow, AVL standard weighing process

Brake Emission PM Repeatability Assessment Takeaways

- A trade-off exists especially for PM_{10} between
  Minimize the sample flow to reduce system's losses (see SAE Technical Paper Nr. 2022-01-117)
  and
  maximize sample flow to increase filter loading
- Minimize the cooling airflow within the defined brake temperature window to reduce "over-dilution".
- By far the most important factor on repeatability of PM is the repeatability of the filter loading.
- Filter handling and weighing process play a significant role and is an important lab proficiency indicator.
- Actual GTR requirements regarding filter weighing (30µg difference between 1st and 2nd weighing) is not sufficient to assure suitable repeatability of the test process.
  Tighter specifications of filter weighing tolerances are necessary and are realistic to achieve.
  Recommendation: Reduce the base value of the allowed difference to max. 10µg being the actual reference filter tolerance (e. g. GTR 15 Annex 6 2.14.3.3 requires reference filters within ±5µg)
- The BW PM filter loading does not significantly change over time, even in an uncontrolled environment.
  Therefore, no necessity for 8h limitation between end of test and filter weighing.
  Recommendation: Relax this limit minimum to 48h as long as the filters are protected against contamination to allow highly automated and efficient testbed operation.