BMW GROUP

BMW MINI ROLLS-ROYCE MOTOR CARS LTD

DISCUSSION DRAFT ON BRAKE EMISSION TESTING

TESTING SETUP AND PROCEDURE PROPOSALS

EF - 70/701

2022-04-27 | BMW AG | Bacher H., Schröder T.

INTRODUCTION

Homologation means that a measured value is compared to a legal limit and the manufacturer must certify the compliance of the product to the legal requirements

⇩

"measuring" becomes "testing"

⇩

a well-defined procedure has to be established and all parts of this procedure must be transparent and traceable to (inter-)national standard

⇩

Testing method must fulfil all prerequisites to achieve legal certainty.
Testing method must ensure a minimum of uncertainty and a maximum of repeatability.

- Certificated accuracy (e.g. ISO 17025, ISO 9001)
- Checked / audited regularly (weekly, monthly, yearly quality checks / calibrations)
- Traceability for all relevant signals must be established

⇩

This is true not only for the testing equipment, but also for procedure and reporting
e.g. R154 Annex B5 3.4.1.1 "The device shall be of certified accuracy."

Today's focus are proposals for certain aspects based on

- findings/results of the ILS
- requirements from other legislations
- technical standard procedures and rules

Discussion draft

CURRENT STATUS

ILS results show differences in "compliance" to current requirements

ILS results show significant inter-lab variability for the same testing object (brake)

ILS shows lower in-lab-variability for different testing objects

Whereas the single setups seems to be quite stable,

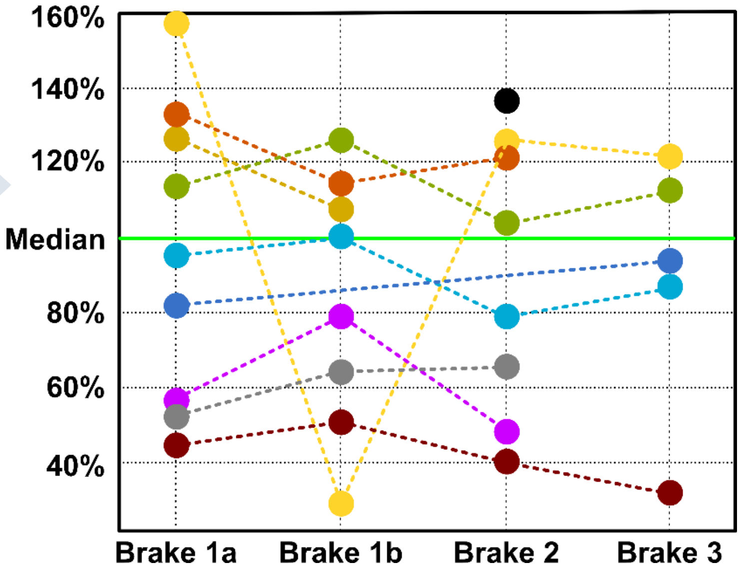
repeatability between different labs is not sufficient

This indicates that there are systematic differences between the labs

These difference limit the comparability of results for the same testing object

Certification of setup and procedure by accredited technical service seems unlikely based on the current data of the ILS

Testing method and set-up is <u>currently</u> not suitable for homologation.



Based on PMP ILS data

Discussion draft

PROPOSAL FOR IMPROVEMENT

Current situation

⇩

If differences between lab are getting smaller, overall uncertainty will get smaller as well

⇩

Proposal within „the specs“ of the observed boundaries of the ILS
➔ No additional variation to be expected
➔ Due to tighter boundaries, decreasing variation or improved repeatability expected

Discussion draft

Additionally, the following assumptions are taken into account:

- Vehicle / brake manufacturers have to purchase new/additional testing equipment
- Test equipment manufacturers have to design (and build) test benches soon
- "Complying" test equipment" is required soon for development/evaluation of brake systems

Current test benches may still be used
- for R&D and comparison studies

→ Transfer of "data" and know-how on "new generation" of brake dynos

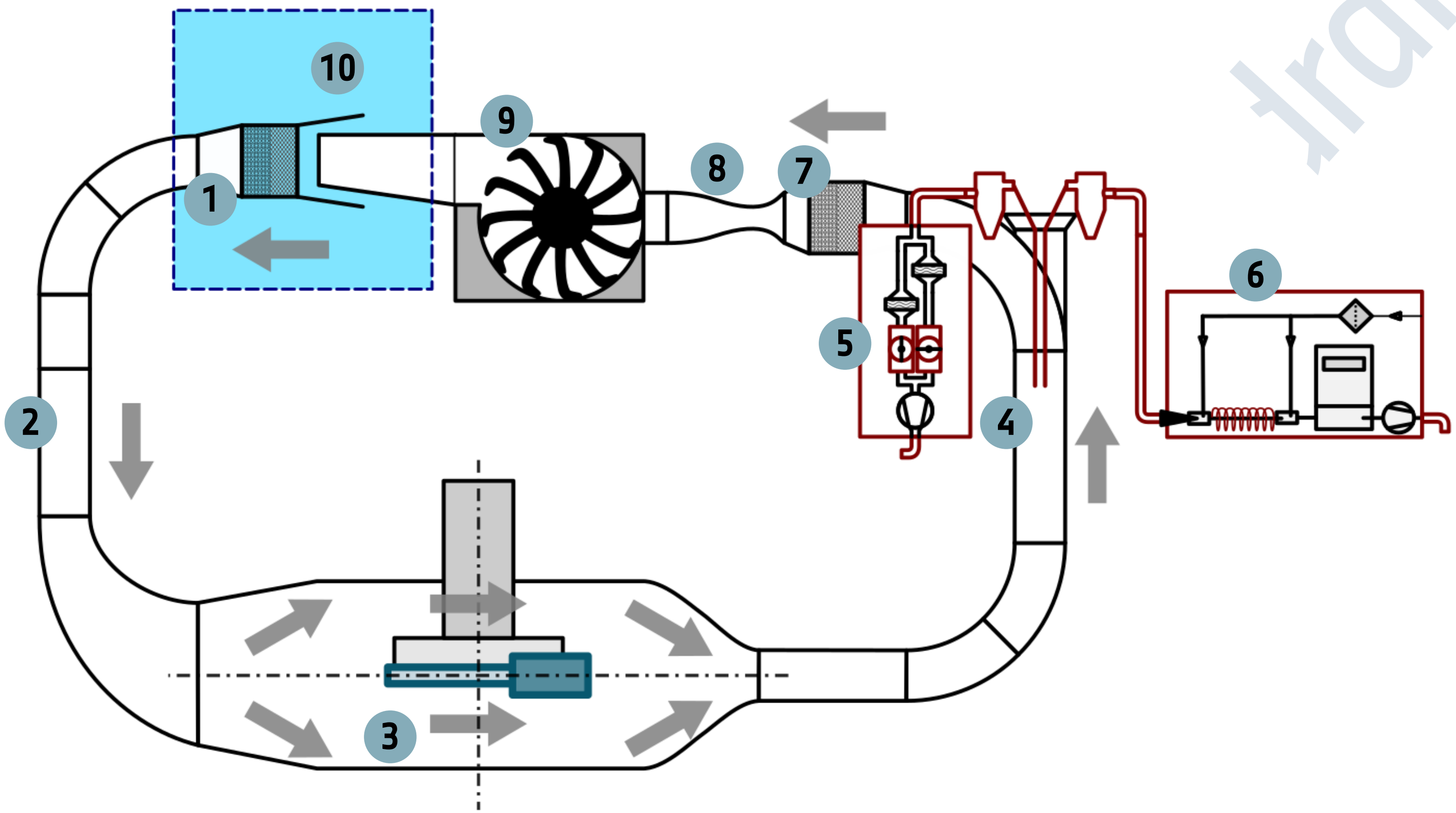
New/additional test benches are required due to:
- Additional demand due to homologation effort

→ There will be additional cost,
but not only due to change of technical requirements.

HOMOLOGATION TEST BENCH DESIGN

Displayed for left brake → direction of rotation such as direction of travel

„top view“

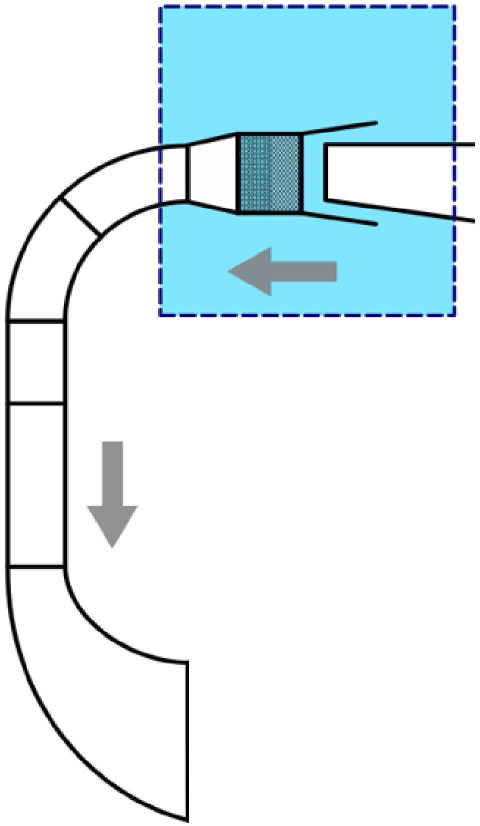


1. Inlet air filtering
2. Intake air system
3. Enclosure / chamber
4. Sampling
5. PM measurement system
6. PN measurement system
7. Filtering / dust removal
8. Mass flow / volume flow control
9. Blower / Air supply
10. Air-conditioning

*Dimensions and arrangement for illustrative purposes only

Draft

AIR INTAKE & CONDITION



<u>Filter Unit</u>

- HEPA Filter
- (Charcoal / active coal– filter required for total PN Measurement)

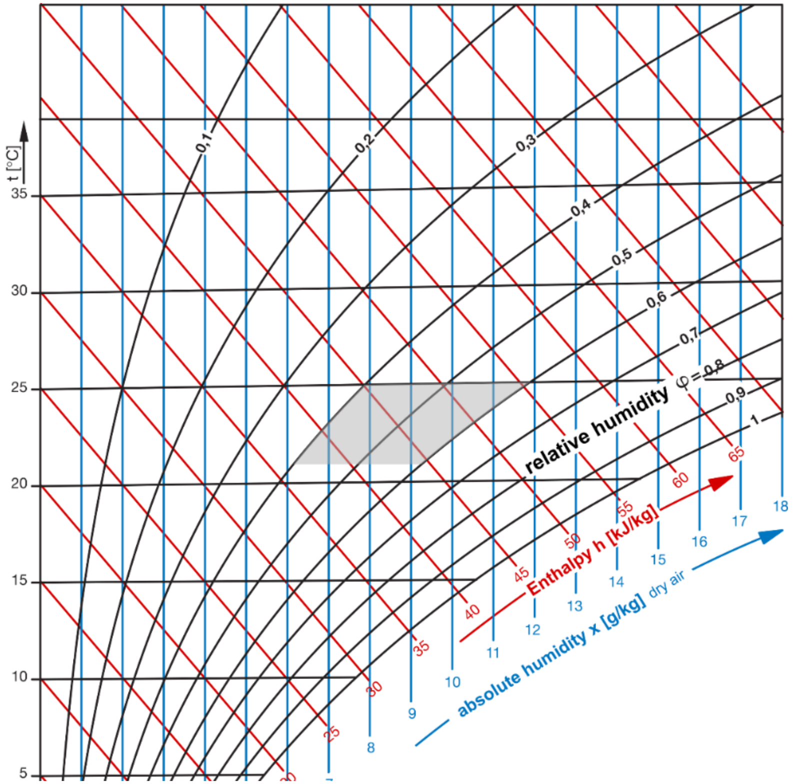
<u>Intake Design</u>

- No special requirement for geometry
- electrically conductive

<u>Air Conditioning</u>

- 23±3°C (WLTP exhaust)
- Measuring of relative and controlling of absolute humidity (industrial standard)

→ absolute humidity has advantages in terms of control quality



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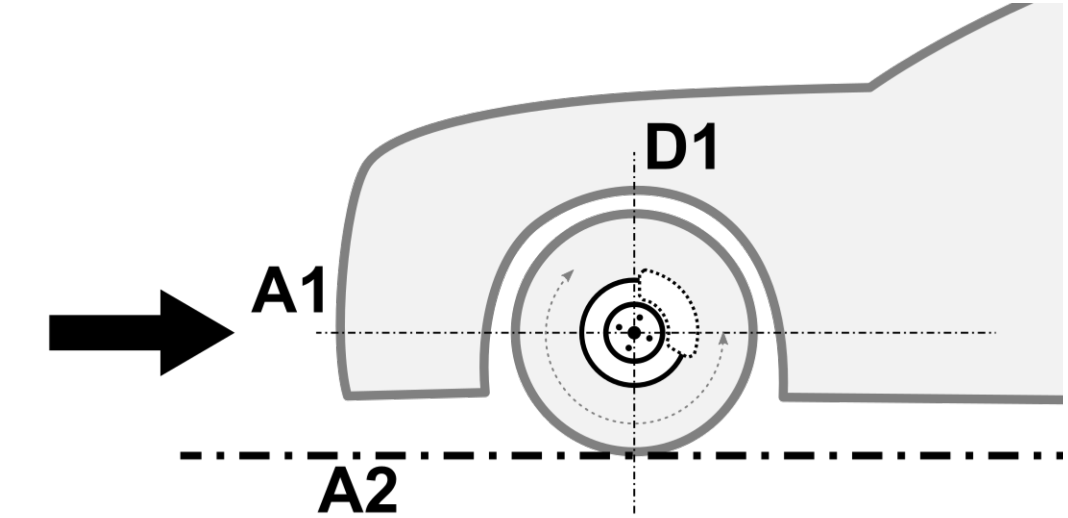
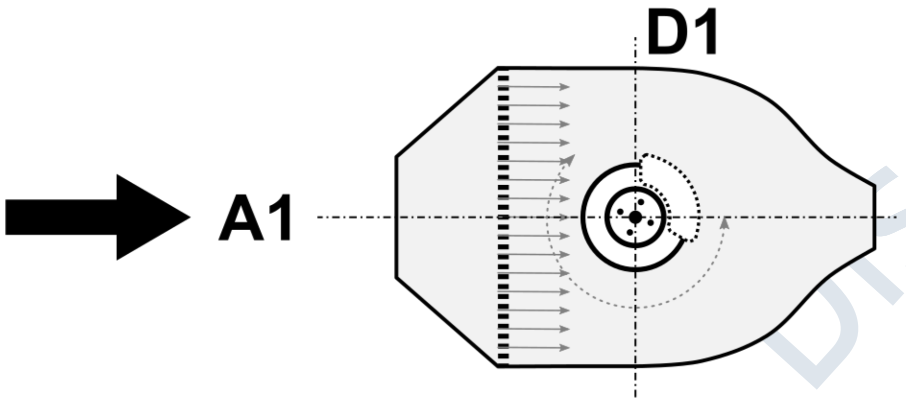
23±3°C air / "ambient" temperature would allow to transfer non-friction-brake vehicle characteristics to "vehicle model" on brake dyno

GENERAL GEOMETRIC DEFINITIONS





<u>Definition of geometric boundaries</u>

A2: road: horizontal plane of the vehicle / ground level

A1: shifted parallel to A2 to the centre of the brake (horizontal)

D1: orthogonal to A1 at the centre of the brake (vertical)

(centre of brake = axis of rotation)

<u>Definition of the enclosure</u>

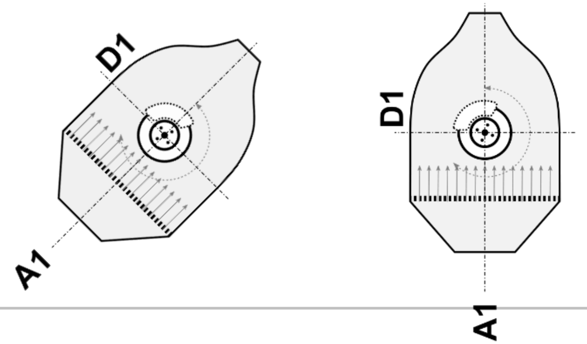
A1: representing horizonal direction (direction of flow)

D1: representing vertical direction (cross-section of enclosure)

<u>Enclosure orientation</u>

Horizontally mounted for easy access and handling

In principle rotation of „overall system“ is possible



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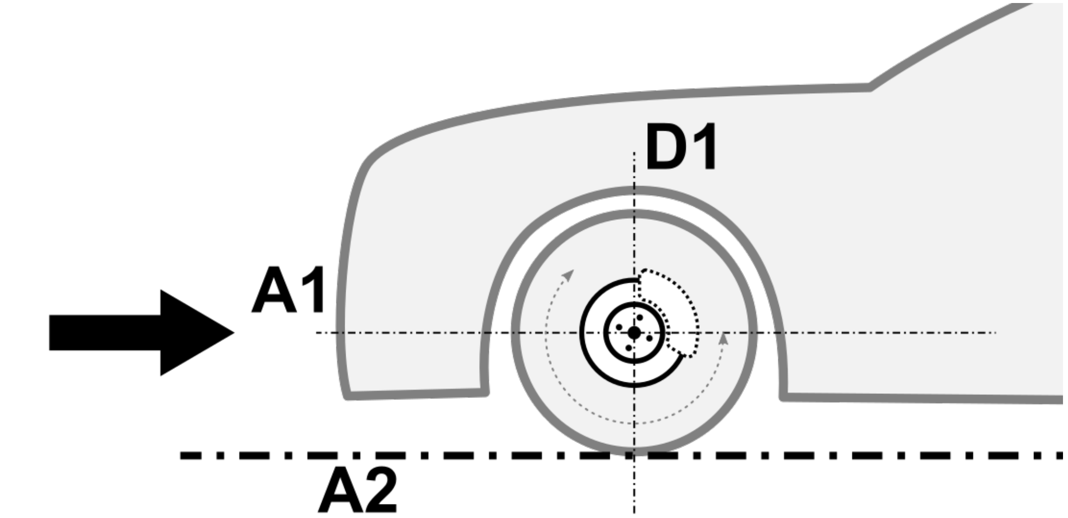
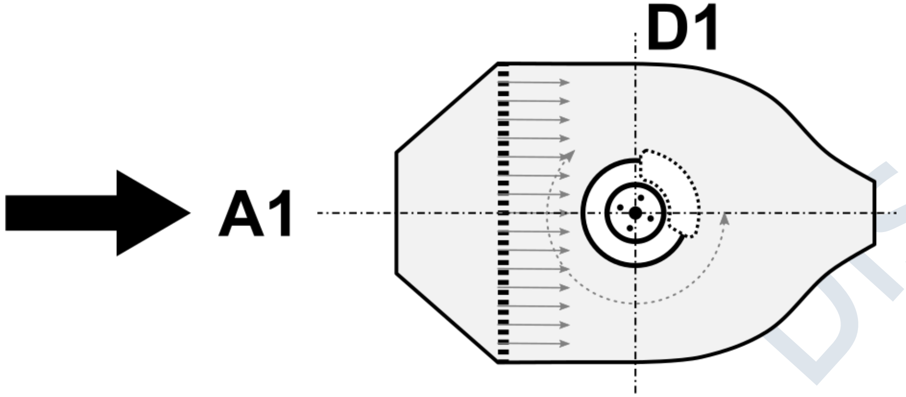
CALLIPER POSITION





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Definition of calliper position

- Position and incoming flow of the calliper as in the vehicle

→ Direction of rotation of the brake as in the vehicle

→ No differences between rear brake and front brake (both same as in vehicle)

→ comparability to real temperature conditions and particle emissions of actual vehicle with regard to on-road behaviour

→ For similar driving the brake domain is driven by the flow regime and not by the temperature regime

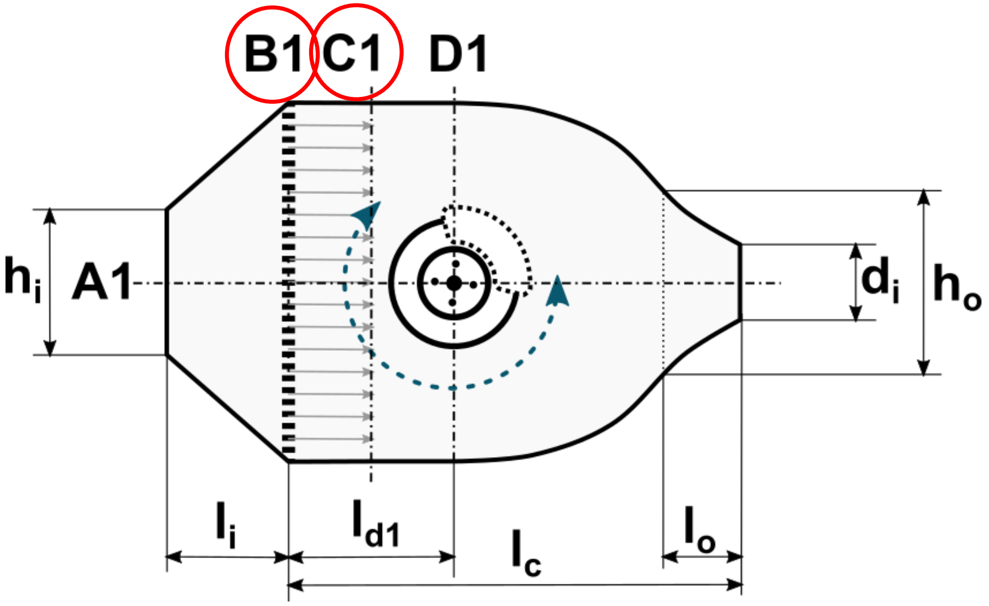
→ For lab measurements air-flow and ambient temperature must be represented

Enclosure design

- Traceable methods for air-speed / direction calibration and regular checks must be established.
  If the flow in the enclosure is non-homogenous, also the "spot of interest" must be defined (e.g. for particle introduction)

Design/shape on the right of D1 still to be discussed (curve / straight) (simulation on-going)

ENCLOSURE DESIGN & RECOMMENDATIONS



The drawings show examples of some dimensions as a basis for discussion.
From our point-of-view stable and comparable measurement results require a standardized enclosure.

There is more work to be done, but some definitions and numbers are presented:

<u>Definition</u>

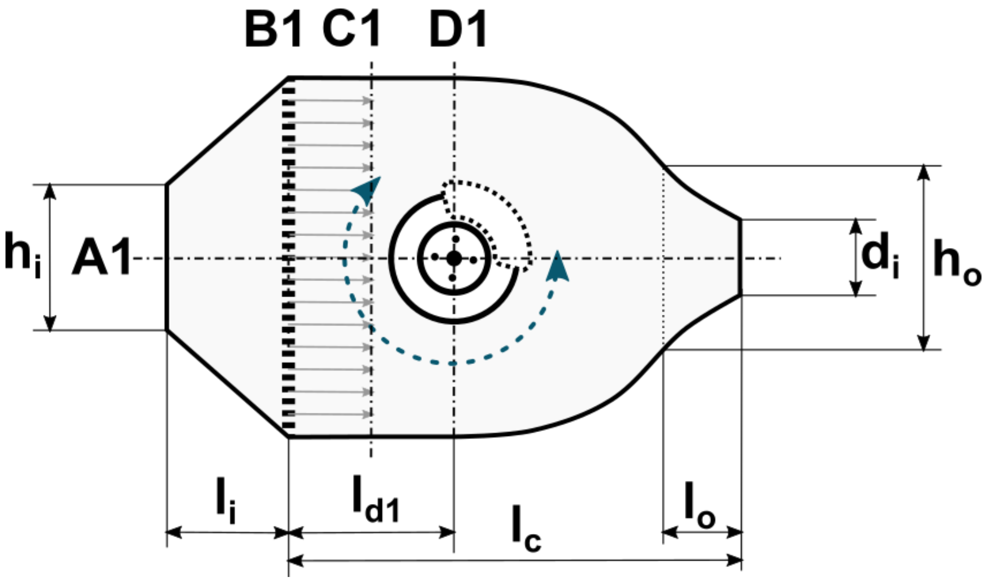
B1: Intake plane with mandatory flow-straightener

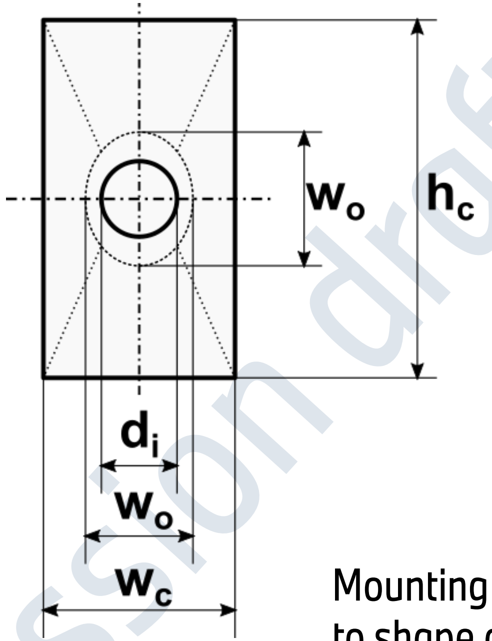
C1: Plane for flow calibration, defined with distance to centre of rotation, based on largest possible disc.

<u>Flow-straightener</u>
To reduce the influence of the air-intake, a flow-straightener should be installed at plane B1.
It creates „parallel / homogeneous flow" which allows calibration/check for flow velocity in plane C1
→To be checked, if method similar to R154 (WLTP) Annex B5 may be applicable.

Discussion draft

ENCLOSURE DESIGN & RECOMMENDATIONS

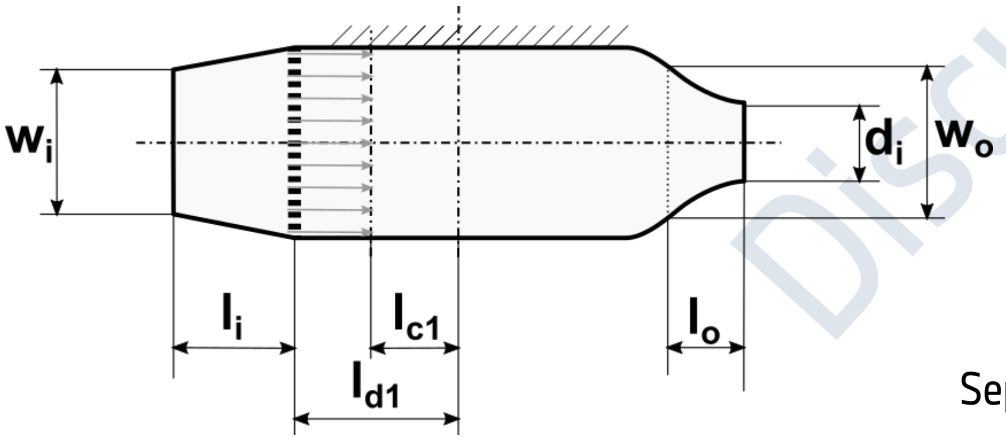




Functional provision proposals:

- Height, width and length are defined based on the largest applicable disc to ensure that all brakes fit into the same design
- Common geometry and set-up would allow for common traceable calibration / validation method

Mounting plane of brake system should be defined with respect to shape of enclosure , A1and D1(input of test equipment manufacturers required)

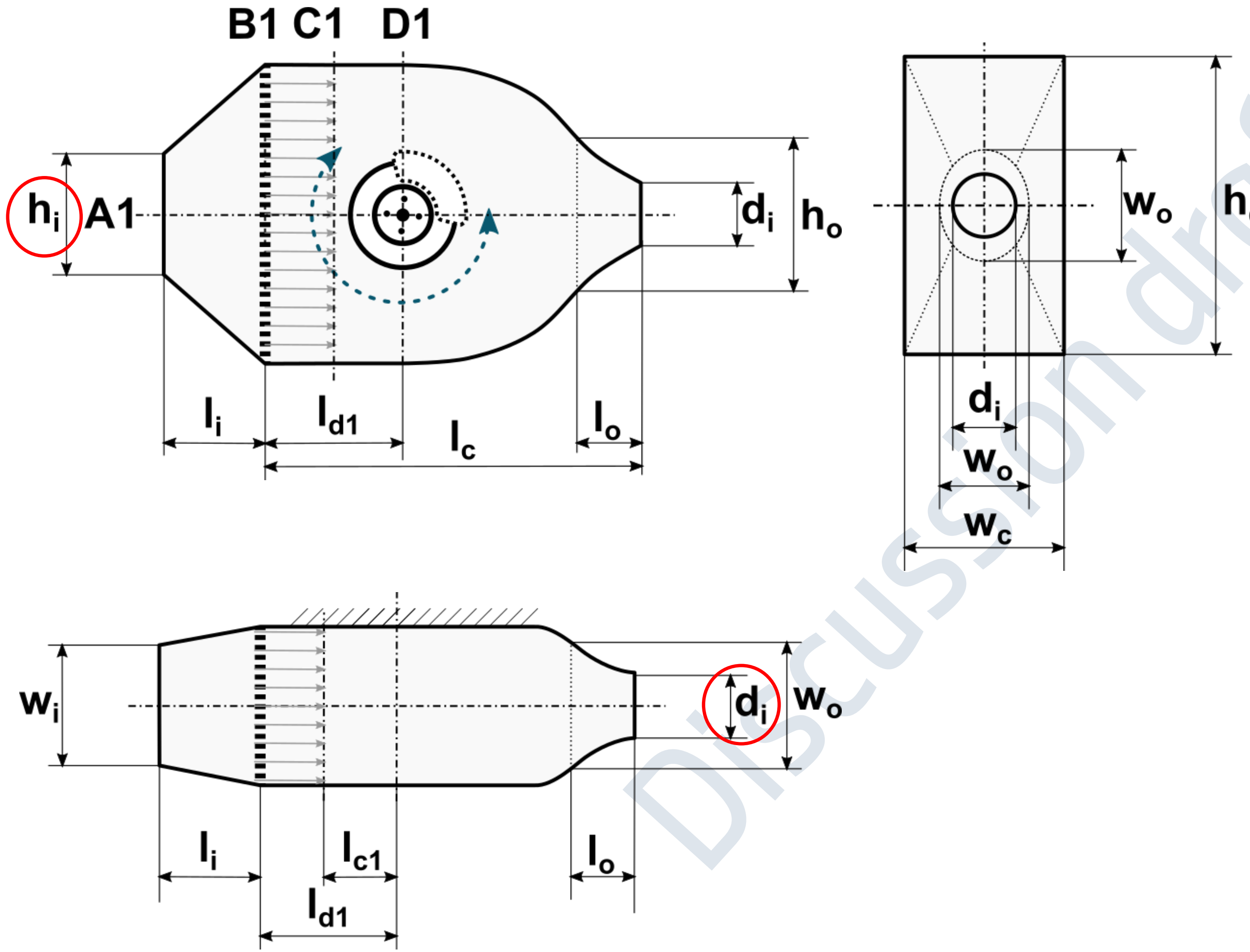


- stainless steel
- electrically conductive
- electropolished surfaces on aerosol facing sides

Separable parts for assembling / disassembling brake system

Discussion draft

ENCLOSURE DESIGN & RECOMMENDATIONS



Discussion draft

Proposed dimensions

h_c: height of the enclosure
1,5 x largest disc diameter (e.g. 700mm)

l_c: length of flow section
≥ h_c (e.g. 700mm)

w_c: width of enclosure
depending on shaft/mounting design

h_i,w_i: dimensions of the inlet
(depending on flow and decision on B1)

l_{d1}: distance between B1 and D1
≥ 1,5 x largest disk radius (e.g. 350mm)

l_o, w_o, h_o: depending on enclosure layout
h_0=0.5 x h_c, w_0=0.5 x w_c

d_i: inner diameter of sampling duct/ outlet air section

If a flow-straightener is installed, there are no special requirements on the geometry of the intake air system.

OUTLET AIR SYSTEM

Discussion draft

SAMPLING POSITION

<u>Requirements on isokinetic sampling:</u>

ISO 9096 „Stationary source emissions — Manual determination of mass concentration of particulate matter" clause 6.2.3:

e) obstacles related to the sampling equipment are:

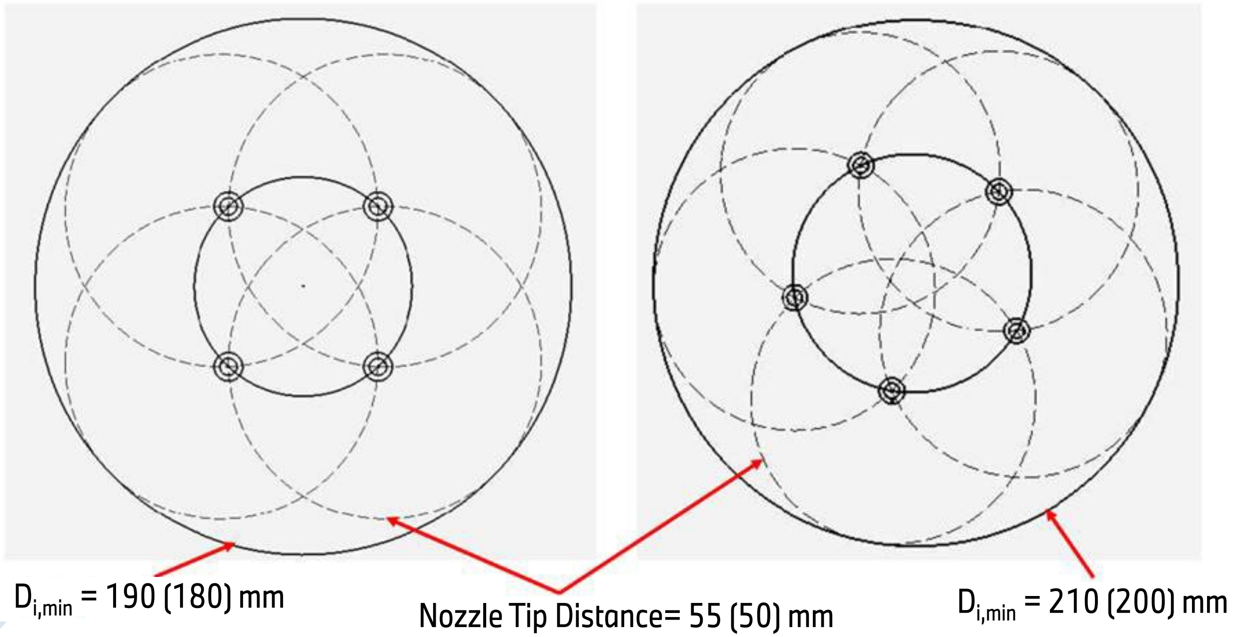
1) prohibited upstream of the nozzle tip;
2) allowed beside and downstream of the nozzle tip, when situated at more than 50 mm or at least one time the size of the obstacle, whichever is greater.

➔ PN and PM sampling must be in the same cross-section area

However, the ISO does not exactly define the nozzle tip.
Is it the centre of the nozzle (fixed)?
or the edge of the nozzle opening (variable with nozzle diameter)?

<u>Calculation of nozzle tip distance:</u>

	50 mm distance from outside of one nozzle to obstacle
+	2 mm nozzle wall thickness (estimate)
+	3 mm nozzle radius/inlet radius (estimate)
=	55 mm

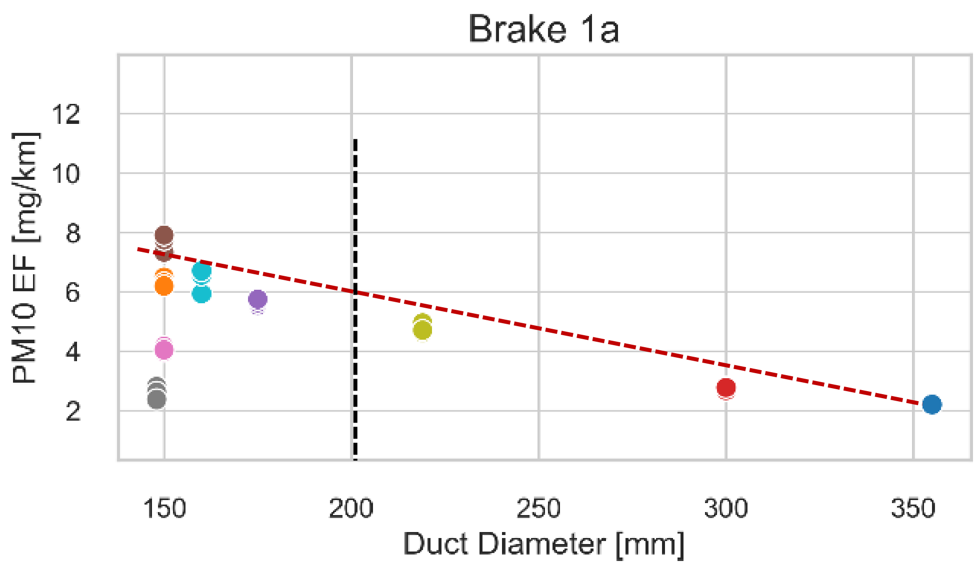


According to this specification and assuming that the following setups are to be used:

- 4 x Nozzle-Setup (left):
  2x PM (2.5 & 10) und 1x PN (solid) with one additional nozzle for enhanced measurement equipment
- 5 x Nozzle-Setup (right):
  2x PM (2.5 & 10) und 2x PN (total and solid) with one additional nozzle for enhanced measurement equipment

Discussi

DUCT DIAMETER



PM10 EF [mg/km]

The ILS Data indicates a correlation between duct diameter and transport efficiency.

But all values are within the scatter band of the “150mm setup”

➔ Stricter requirements are necessary to improve comparability

➔ No preferable diameter can be identified based on the emission data

Discussion draft

<u>Influence of the duct diameter on the flow velocity</u>

- If it is too large, we have negative effects due to low flow speed affecting brake temp and transport efficiency
- If it is too small, we have negative effects for isokinetic nozzle diameters due to high flow velocities, as we have to choose smaller nozzles and less sampling probes.

DUCT DIAMETER AND COOLING AIR SPEED

Proposal:

Constant duct diameter (200 mm)

Closed Issues:

- Nozzle Tip Distance (ISO 9096)
- Reasonable cooling air speed/flow ratio
- Similar loss characteristic
- Accessibility for cleaning
- Commercially available standard size

$Q_{tunnel\text{-}Flow}$ [m³/h]	$Q_{tunnel\text{-}Speed}$ [m/s]	$d_{Nozzle\text{-}5LPM}$ [mm]	$d_{Nozzle\text{-}8LPM}$ [mm]	$d_{Nozzle\text{-}10LPM}$ [mm]	$d_{Nozzle\text{-}16,7LPM}$ [mm]
790	7,0	3,9	4,9	5,5	7,1
900	8,0	3,7	4,6	5,2	6,7
1020	9,0	3,4	4,3	4,9	6,3
1130	10,0	3,3	4,1	4,6	6,0

*possible cooling air flow/speed setups

Open Issues

- Isokinetic Sampling:

  Minimum 4 nozzles for each cooling air speed setup

  → high number of nozzles required

  e.g. 4 nozzles * 4 Setups = 16 nozzles per test bench

  → high cost factor

  → high tracking effort (traceability for homologation)

- Cooling air speed:

  Controlling of various cooling air streams required

  → high control quality of the cooling air flow required

  → high control quality of the climate control required

  → unclear effort and cost for calibration
  (how many speeds and flows to be investigated)

discussion draft

DUCT DIAMETER AND COOLING AIR SPEED

Proposal:
A fixed and defined cooling air flow

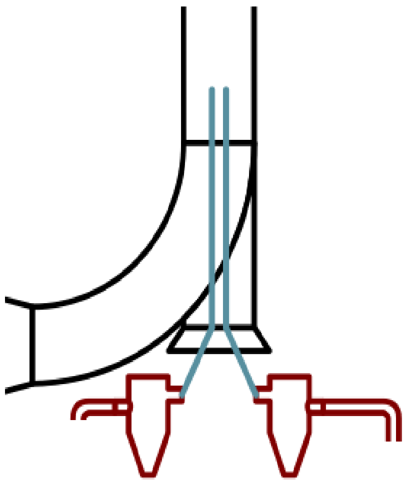
Closed Issues
- Isokinetic Sampling
- Nozzle traceability
- Air flow traceability (if a CVS is used)
  → "Constant" air speed (air conditioning)

Open Issues
- Cooling air adjustment still necessary?
- Temperature Boundaries still necessary?
  (lower temperature defined by air-conditioning, upper temperatures defined by air-flow)

Q_{tunnel}	v_{tunnel}	$d_{Nozzle\text{-}5LPM}$	$d_{Nozzle\text{-}8LPM}$	$d_{Nozzle\text{-}10LPM}$	$d_{Nozzle\text{-}16,7LPM}$
[m³/h]	[m/s]	[mm]	[mm]	[mm]	[mm]
1130	10,0	3,3	4,1	4,6	6,0

Discussion draft

SAMPLING



PM Sampling:

- Only one cyclone with defined cut-off per sampling line (PM2.5, PM10)
- Cyclone position directly at nozzle probes (minimizing of losses and pollution in tubing)
- Constant tubing diameter before/after cyclone
- Tubing length & geometry according to ISO 9096
- Bending diameter between cyclone & filtering unit $r_{b\text{-Tubing}} > 25^* d_{i\text{-Tubing}}$
- Calibration / loss factor determination with cyclone and tubing included (to be discussed)
- Sampling flow between 8 – 17 LPM due to cyclone design/availability
- 17 LPM is preferred due to too low loading especially when regen braking etc is taken into account

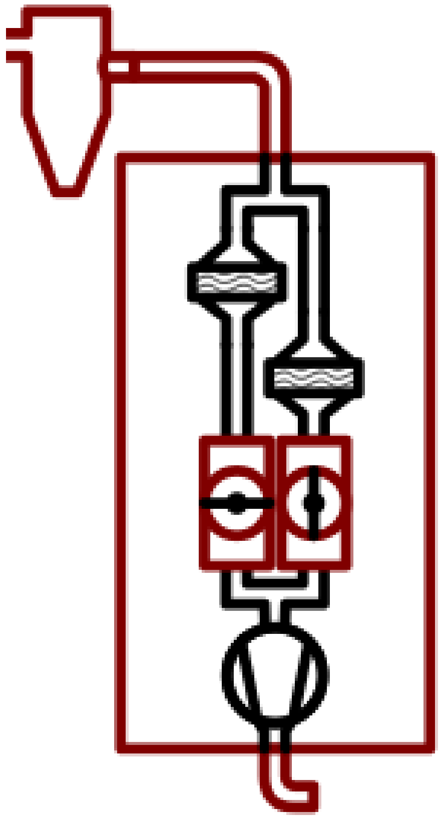
PN Sampling:

- Only one cyclone (as pollution protection) with defined cut-off per sampling line
- Cyclone position directly at nozzle probes (minimizing of losses and pollution in tubing)
- Tubing length & geometry according to ISO 9096

Installation of the nozzle probes in 90° duct bend due to mounting / accessibility etc.

Discussion draft

PARTICLE MASS MEASUREMENT



<u>Proposal:</u>

Gravimetric filter method as single method for determination of PM

- Traceable and established procedure (see exhaust PM)
- No method for traceable calibration of impactors known

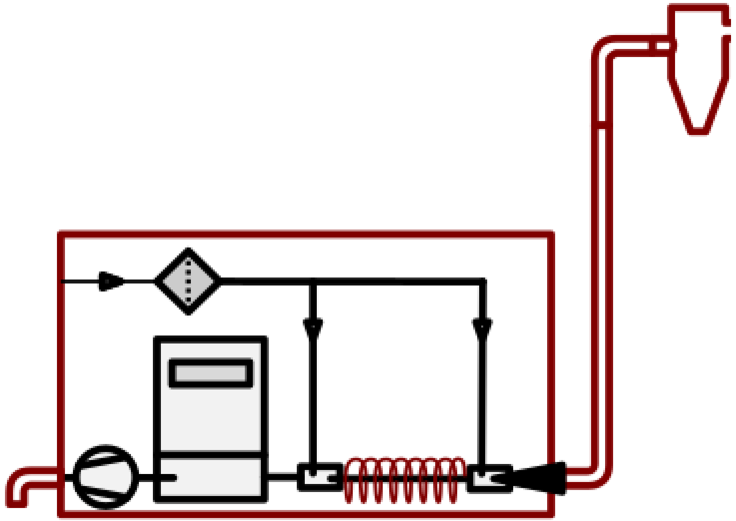
At least two sequential filters e.g. for PM measurement:

- Possible averaging to improve accuracy
- Check whether bedding is sufficient
- Automated operation without manual intervention for sequential testing

- Design of the “splitter” to be optimized by test-equipment-manufacturers
- Back-flush / bypass / switch-off capability required due to bedding or soaking (not in illustration)

Discussion draft

PARTICLE NUMBER MEASUREMENT



Proposal:

- No significant share of volatiles observed (ILS-presentation of Mamakos et al.)
  →Measuring only solid PN
  →No charcoal filter required of setup
- Fixed dilution 1:100
- catalytic stripper
- complete-system approach (due to system calibration, homologation requirements)
  →Calibration laboratories / procedures already available

Leak check of air system via PN background check possible, if the setup is operated under "negative" pressure

Response check of PN system required (open enclosure?)

Determination of a overall "PCRF" required for solid "PCRF" determination for total(?)

Discussion draft

PCRF: particle counting reduction factor (loss correction, see exhaust legislation)

COOLING AIR FLOW CONTROL

Proposal:

Operation of test bench in a slight vacuum / negative pressure
(worker safety / health requirement, leak check capability,….)

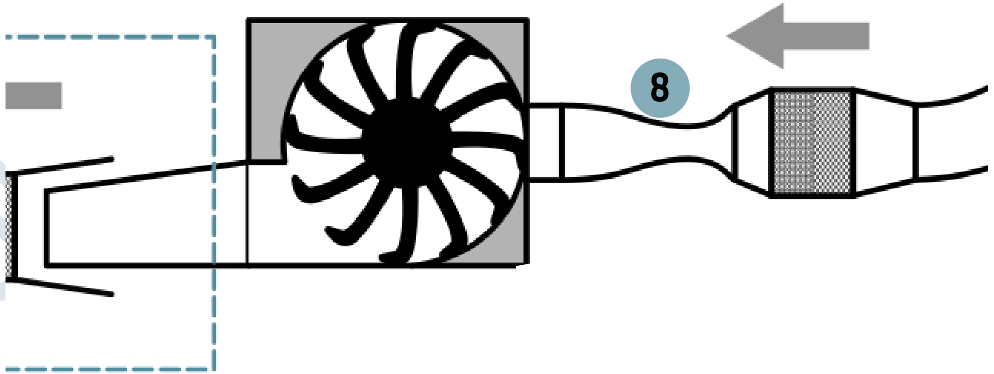
Pre-filtering before flow measurement (pollution prevention)
as flow-measuring / control is downstream of sampling

Instead of flow control use of one critical nozzle
(CVS principle as established in exhaust legislation)
→ Calibration procedures, traceability can be transferred from exhaust legislation
→ Calibration and traceability of other methods must be described in detail
→ Using a single volume flow requires only one isokinetic nozzle size per PM/PN-device
→ minimum documentation effort and error influence
otherwise, a proof of installation for each nozzle is required
(no idea how to do that)

Measurement of pressure and temperature
→ Standardization / Normalisation of volume flows

Fixed humidity and temperature (e.g. 23±3°C) comparable to exhaust legislation:

- Defined starting conditions for brake
- Improved transferability of regen (and other) measures from vehicle to test bench
- Dew point below 11°C to avoid condensation



Discussion d

CLOSED/OPEN ISSUES

Closed issues with proposals

Flow regime at enclosure entrance

Health / worker safety
(in terms of nano particles and ergonomics)

Air flow variations

Isokinetic sampling and handling

Sampling flow variations

Flow calibration (enclosure and total)

PM/PN variations

PM/PN calibration

Accessibility for cleaning

Similar loss characteristic

Difference between WLTP Exhaust and WLTP Brake

ISO 9096

(still) open issues

Final geometry of enclosure

- Additional input on concept required
- Details to be finalized after concept decision

Enclosure burst protection (safety)

Cooling air adjustment still necessary?

Temperature boundaries still necessary?

Overall loss determination / loss factor required?

PM/PN correlation method between test benches

Nozzle tip definition

Discussion draft

HOW TO MEASURE BRAKE EMISSIONS (FAST)

Final Version of GTR

→ Definition and ordering of test benches

→ Development of test benches

→ Building of test benches

→ Delivery of test benches

→ Acceptance tests

→ Start of Testing (SOT)

Availability

Planning time

Due to legal relevance:

- Proof of testing / inspection process capability (DIN EN ISO 14253-1:2018-07; DIN EN ISO 9000; DIN EN ISO 9001)
- Determination of testing system suitability and capability (e.g. DIN EN ISO 22514-7)
- See also industrial standard: VDA Volume 05: Capability of Measurement Processes

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→ Certification of test process / equipment by technical service / authority (based on previous step)

→ Reliable measurements for development and homologation

→ Fulfilment of product conformity and liability

Discussion draft

SUMMARY

- Everything in the presentation is to be understood as a suggestion
- With "good engineering judgement" we do not see any weakening of the current situation in any of the adjustments to the current status
- Potential for unification (and simplification) is presented
- Optimization of “overall procedure” for industrial testing
- **Discussion contributions are welcome**

Topics, which need to be addressed, but are not covered during this presentation:

- Background check (PN)
- Response check (PN)
- Sample flow checks (PN/PM)
- Test end cleaning / flushing provisions (before opening)
- Cleaning intervals and scope
- Correction of sampling flow ?
- Validation of “driven distance” ?
- ...

Discussion draft

THANK YOU VERY MUCH FOR YOUR ATTENTION

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