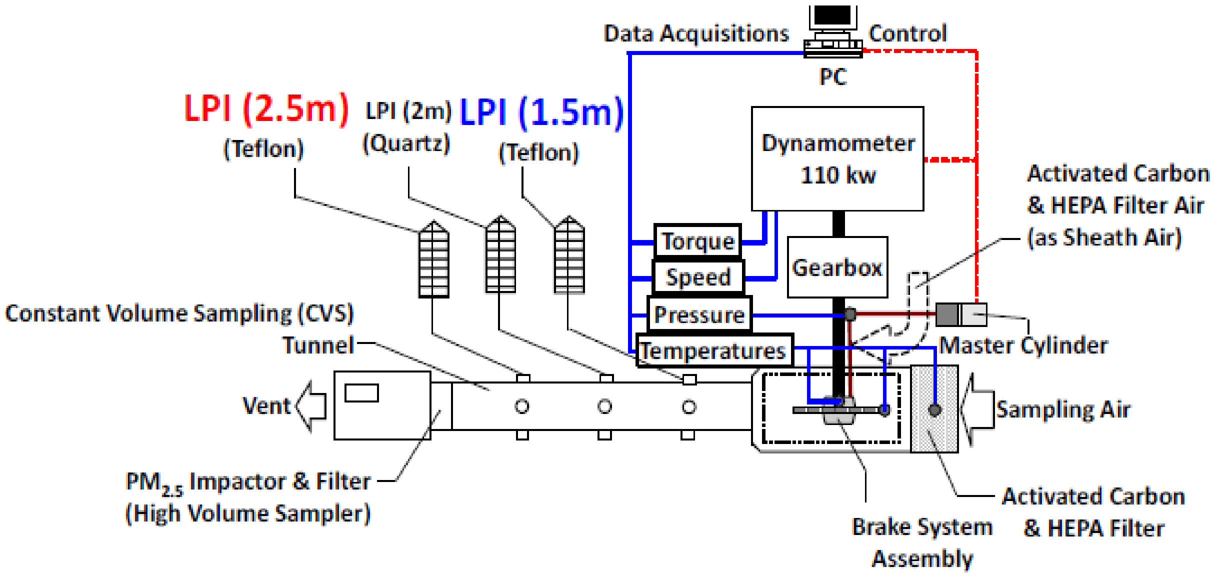
Existing configurations and related uncertainties

The document provides information on currently available brake dyno setups and consist of two parts. The first part aims in giving a short description of each set-up and its fundamental characteristics. Not all details are described but only the main features. Information on the configurations found in JARI, TU Ilmenau, Ford, Horiba-AUDI, Brembo and GM is provided.

The second part includes the tables which provide the technical specifications, the parameters which can be related to uncertainties as well as the estimation regarding related losses. More specifically, Table 1 features identified uncertainties related to the technical specifications of the configurations, Table 2 focuses on other related uncertainties (i.e. flows, residence time of particles in different compartments, etc.) while Table 3 provides a rough description of the related losses due to different phenomena.

1. JARI Design

It is a Constant Volume Sampling (CVS) tunnel based methodology. Air flowrate is set at a constant value (0.5-1 m^3/min) and sampling of the particles takes place directly at the CVS tunnel. Filtered air in the temperature range of 20±5ºC and RH lower than 35% is used for the dilution. A high volume impactor is attached at the end of the tunnel for PM_{10} or $PM_{2.5}$ concentration measurement. Filters are used for the collection of the particles and subsequent chemical analysis. Other instrumentation for PN (CPC, OPS, APS, EEPS, ELPI+) is mounted in the middle of the CVS tunnel (different locations are possible).



Regarding measurement efficiencies and related uncertainties it was shown that increasing sampling air flow rate results in overall lower PM (DustTrak II 8530 corrected by gravimetric measurement) and PN (TSI CPC 3775 (D50 = 4 nm) without pretreatment) concentrations (mg/m^3) both for LS and NAO materials. Higher air flowrates close to 4 m^3/min lead to PM and PN concentrations close to the higher uncertainty region. Since it was shown that there is no significant difference of total mass emissions per test with flow rate it is recommended that low flow rates are applied (0.5 mg/m^3).

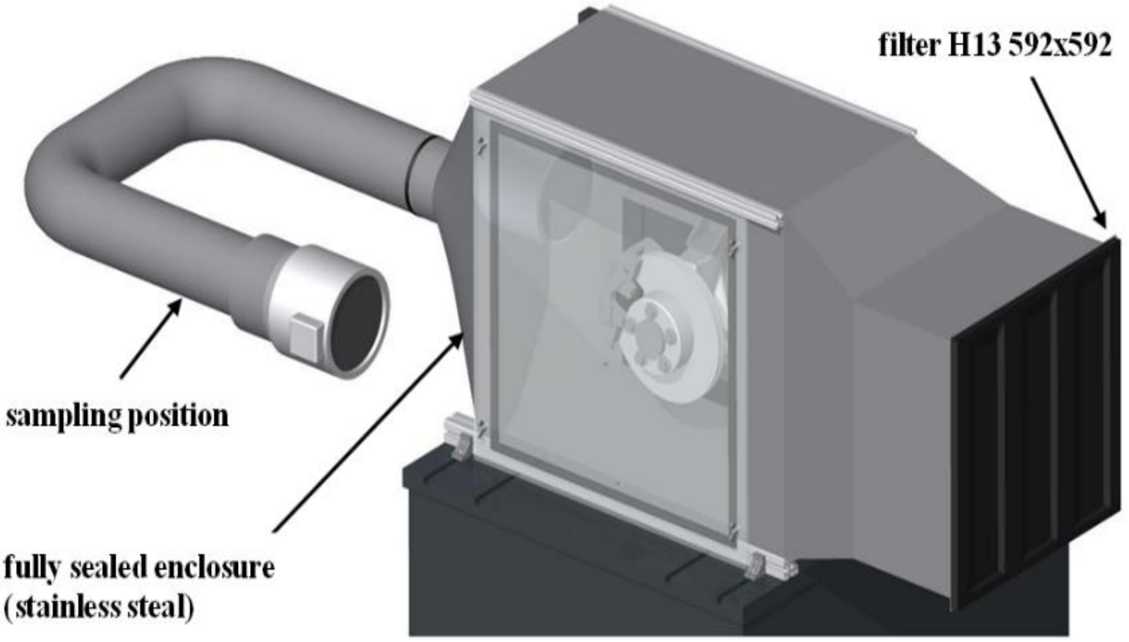
For a selected flow rate of 0.5 m^3/min (0.05 m/s) the residence time is less than 25s and it has been shown that for mass size distributions measured with Low – Pressure Impactors the sampling distance from the box doesn't play a significant role (similar distributions for distance 1.5 and 2.5 m). Also despite the high residence time a good correlation between PM and PN emissions per km was found for the WLTC cycle. This may be due to the low total PN concentrations (<10^7 #/cm^3) where agglomeration is negligible.

Study regarding the particle collection efficiency showed very high efficiency for almost all size ranges. Only for particles bigger than 5 µm the efficiency decreases to 90%.

2. TU Ilmenau Design

The system is a Constant Volume Sampling (CVS) tunnel based methodology. In this case the air flowrate is set to a constant value and sampling of the particles takes place directly (partial volume) at the transport line. Filtered air is used for the dilution while a fully sealed chamber ensures a minimized background concentration. A multi-device-measurement approach is followed with the use of a flow splitter.

TU Ilmenau Sampling system 1 - PM2.5-setup



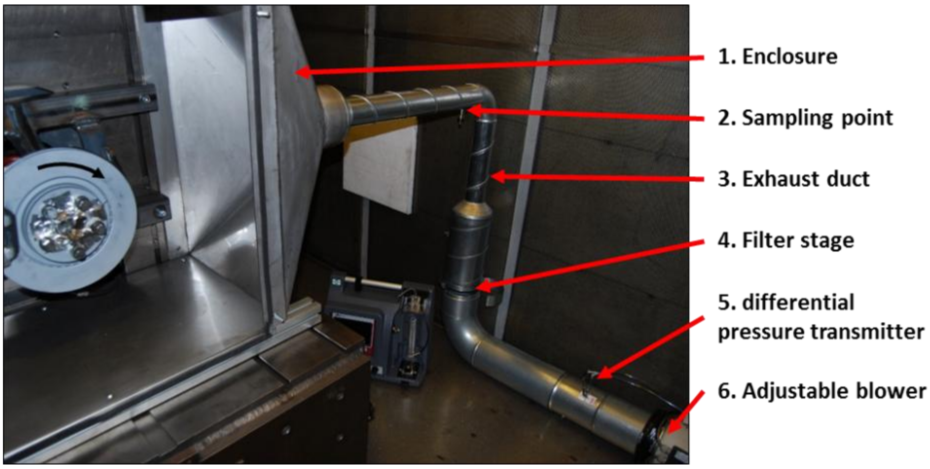
Chamber inlet and outlet are designed in such a way that transport efficiency is maximum. The CFD based design results in a low residence time of particles in the chamber (~3s). A U-shaped measurement tunnel is used to generate additional longitudinal vortexes which helps improving the uniformity of the particle loaded flow.

CFD based results show a strong dependence of transport losses and particle uniformity from the air volume flow, suction direction and disc rotation speed. CFD studies indicate that evacuation in reverse particle stream direction with maximum air flow is preferable to ensure maximum particle mixture, transport efficiency and “cooling of the brake-system” at the same time. The only variable parameter during the measurement is the disc rotation speed. Centrifugal forces determine the initial particle velocity which effects particle deposition and uniformity. At lower speeds uniformity across the measurement tunnel diameter may be restricted (~80%) for 0-30km/h. For 60-150 km/h the particle spread can be considered uniform (>90%). Additionally, CFD simulation offers the possibility to assess the transport efficiency of the CVS depending on the test-cycle velocity profile.

A study regarding the particle collection efficiency showed transport efficiency optimum between 0.01-1µm. Below 10nm diffusion losses and above 1µm inertia losses are observed. Due to impaction and sedimentation, sufficient measurement of particles > 2.5µm are characterized by increased losses.

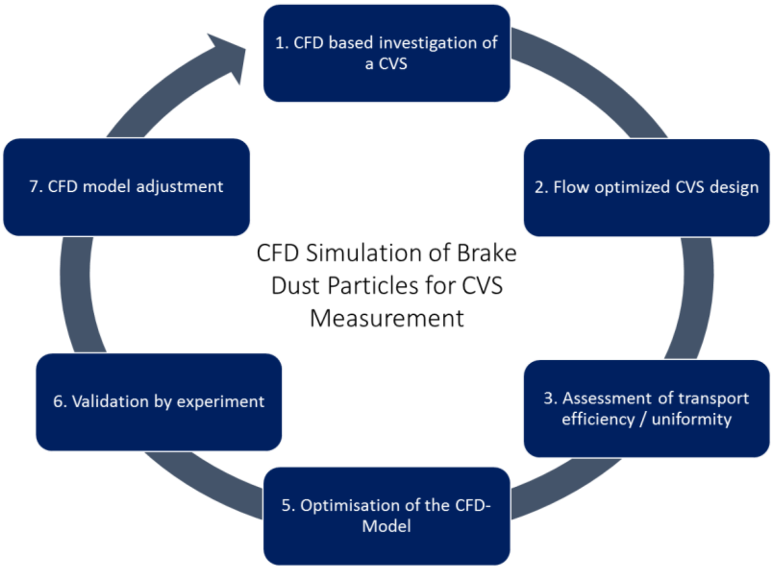
The PM10-setup allows the measurement of particles up to 10µm with a high efficiency and reasonable uniformity. The diameter of the exhaust air duct is 8cm, the length to the sampling point is 56cm. In addition, a filter stage is integrated in the exhaust duct, which allows directly to investigate the transport efficiency (mass-based) according to the method presented below.

TU Ilmenau Sampling system 2 – PM10-setup



Concept Development to Investigate the Transport Efficiency of Sampling Systems

The determination of transport efficiency has limited validity using existing tools (e.g., Particle Loss Calculator / PLC) in which flow rates and pipe geometries can be specified. In particular, in the case of complex geometries (brake system including wheel carrier) and complex flow, the PLC is not validated. In particular with regard to the calculation of inertia losses. The application of complex software for the implementation of mathematical-physical models (user-defined flow models), whereby a high quality of results can be achieved, provides a necessary alternative. The challenge is the implementation of physical properties (e.g., the real size distribution, particle density, Hamaker-constant, minimum contact distance, restitution coefficient, etc.). CFD modeling allows a real simulation of particle-particle interaction and particle Wall interaction as well as inertial deposition, diffusion / turbulent diffusion, etc. The TU Ilmenau is developing such mathematical-physical models for inertia-dyno and RDE-sampling systems, which are currently in the validation process.



For the experimental validation of the transport efficiency of a sampling system and the determination of the deposited particle sizes, the following concept are used:

Step 1: Validation of the Transport Efficiency of Sampling Systems

The concept describes a procedure for determining the transport efficiency (by establishing a mass balance) of sampling systems based on experimental investigations. For this purpose, the particle mass deposited (not evacuated) on different components within the sampling system (enclosure, exhaust duct, etc.) is weighed and set in relation to the total evacuated particle mass. The concept is applicable to all presented sampling systems in which a particle-loaded flow is evacuated through a defined geometry. The total evacuated particle mass is detected by means of a class M5 filter stage (or better) integrated in the exhaust duct (fine dust filter - particle size range: 0.3 to 10 µm), whereby no special requirements apply to the shape of the pipe or the filter holder. All particles that have passed the predefined sampling position / sampling cross-section are assumed to be evacuated. All particles that have not passed the sampling position are assumed to be deposited. This includes particles that adhere within the enclosure and on the inner walls of the exhaust duct. Particles adhering to the wheel carrier, caliper, disc and pads are determined as a reference, but are not assigned to any of the previous classes (neither evacuated nor deposited). Capturing of the particles deposited in the enclosure is carried out by means of a vacuum cleaner with a filter stage of class M5 or better. The weighing of captured particles is conducted with a precision balance with a readability of 0.001g or better.

The concept provides for the preparation of a mass balance according to the following points:

1. Reference measurement – weighing of the unloaded filter stage (5) of the exhaust air duct and the filter stage of the vacuum cleaner as well as of the disc and pads (determination of the respective individual masses before the start of the test cycle)
2. Adaptation of the weighed brake components and the filter to the predefined position within the cleaned sampling system

   - ➢ Execution of the test cycle as specified

3. Removing of the now particle loaded filter stage from the intended position. Weighing of the particle mass deposited on the filter stage; renewed implementation in the exhaust duct
4. Evacuation of the particulate matter deposited in the exhaust duct after the sampling point; evacuation by means of compressed air and separation on the integrated filter stage; removal and weighing of the filter stage; renewed implementation in the exhaust duct
5. Evacuation of the particulate matter deposited in the exhaust duct before the sampling point; evacuation by means of compressed air and separation on the integrated filter stage; removal and weighing of the filter stage; renewed implementation in the exhaust duct
6. Suction of the particles deposited inside the housing by means of a vacuum cleaner with integrated filter stage (class M5 filter or better); weighing of the particle loaded filter stage
7. Weighing of the used test components (disc and pads) in untreated condition
8. Evacuation of particles adhering to the caliper and wheel carrier; weighing of the filter stage; renewed implementation in the exhaust duct
9. Evacuation of the particles deposited on disc and pads; collecting by means of filter stage and weighing (each individual measurement) to establish the total mass balance

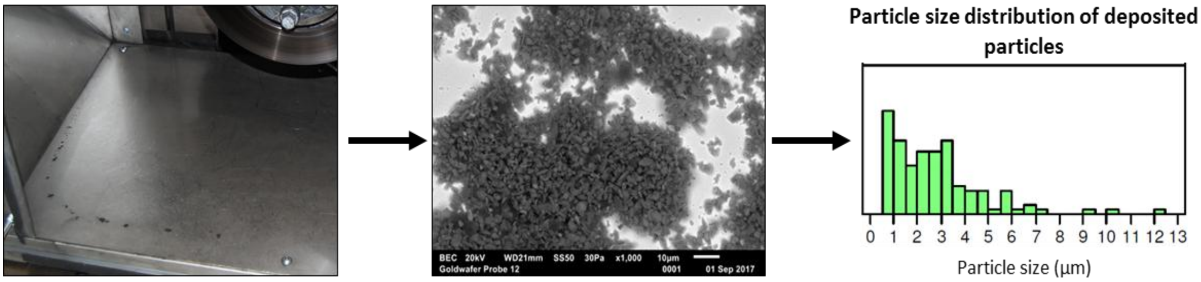
Comparison of the non-evacuated particle mass (deposited within the enclosure and in the part of the exhaust duct before the sampling position) with the evacuated particle mass (deposited on the filter stage and in the part of the exhaust duct after the sampling position. Determination of transport efficiency (mass-related). Comparison of the sum of evacuated and non-evacuated particle mass with the mass loss (disc and pads). Determination of the ratio between loss of mass on disc and pads and the mass gain, which serves as a measure of accuracy. Already performed measurements showed a high reproducibility and a high value of the explanatory loss mass due to the growth weighed at the filter stage. The following table demonstrates the comparison of the particle masses weighted at individual sections:

	mass loss		mass increase					
Description	Emitted mass Disc / pads [g]	Deposited particle mass Disc / pads [g]	Loading filter stage (F5) [g]	Deposited particle mass after sampling pos. [g]	Deposited particle mass caliper and wheel carrier [g]	Deposited particle mass enclosure [g]	Deposited particle mass before sampling pos. [g]	**Σ** **[g]**
value	**2,544** disc: 1,025 [1] pads: 1,519 [1]	**0,066** disc: 0,035 [1] pads: 0,031 [1]	**1,975** [2]	**0,098** [2]	**0,092** [2]	**0,236** [2]	**0,043** [2]	**2,444** **(96%)**
Percentage (mass increase)			80,81%	4,01%	**3,76%**	9,65%	1,76%	
			84,82%			**11,41%**		

The comparison shows that 2.444g (total mass gain) explain about 96% of the total particle mass emitted (2.544g). The calculated transport efficiency for the sampling system amounts 84.82% of total particle mass.

Step 2: Analysis of the Deposited Particle Sizes

The concept includes the verification of particles deposited within the enclosure as well as in the exhaust duct with regard to their size distribution and estimation of the transport efficiency calculated in concept 1 for different size ranges (PM10, PM2.5). In particular, particles larger than 1 µm are the focus of the sampling, as they are characterized by a high deposition rate (due to sedimentation and impaction caused by inertia) and a high proportion of the mass-related transport efficiency determined in concept 1. For this purpose, sampling pads are positioned within the enclosure and in the exhaust duct right in front of the sampling position. Especially in dead water areas, where particles accumulate, adaptation and sampling are necessary. The loaded pads are removed and analyzed by high-resolution microscopes. These particle accumulations are counted by a special software. Therefore, the specific area which is covered by each particle is determined. From the area determination, the particle diameter and a holistic size-resolved number concentration can be estimated. As a result, the entire particle size range (down to the nm range) can be analyzed as a function of the microscopic magnification, and the influence of the separated particles on the transport efficiency (based on mass) can be estimated.



From the knowledge of the size-dependent particle density (sampling by means of Dekati ELPI + and chemical analysis by means of XPS for the determination of the available chemical compounds), a size-resolved particle mass concentration of the deposited particle loads can be estimated.

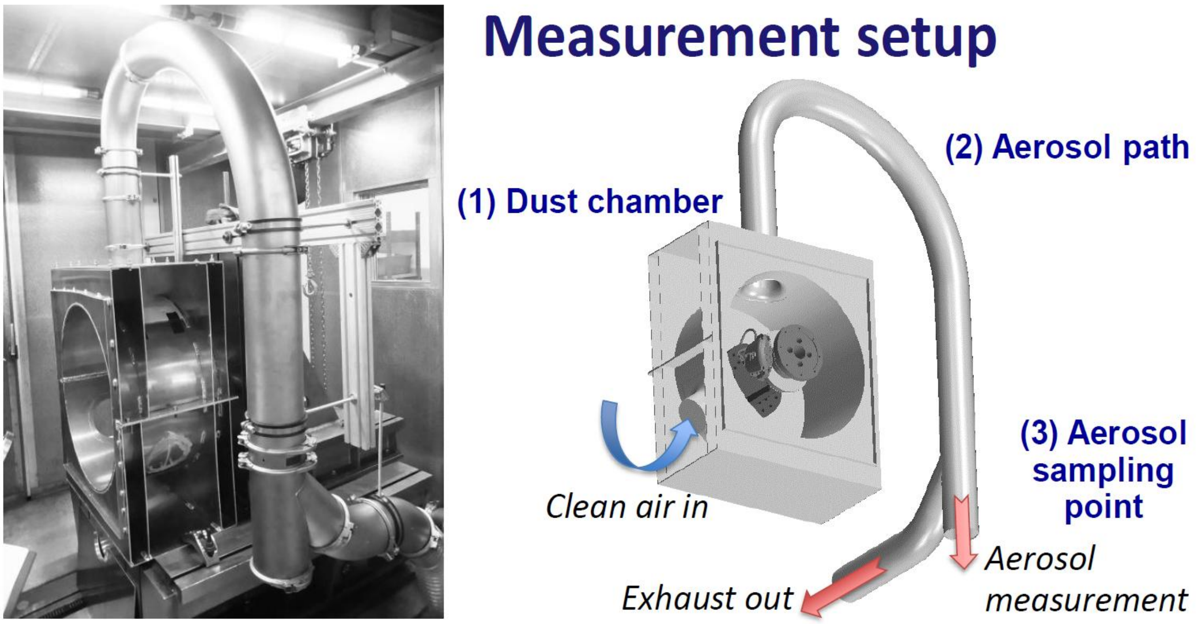
Step 3: Measuring System-Based Analysis of Transport Efficiency

In addition to the particle sampling on pads, a measurement of a size-resolved number concentration is simultaneously carried out by means of suitable measuring technology over a specific size range (for example Dekati ELPI + with a size range of 6 nm-10 µm). As a reference for the size-resolved number concentration measured at the sampling position in the exhaust duct, the sampling at the caliper outlet is carried out by means of an adapted sample box.

This allows a comparison of size-specific losses based on particle measurement. With knowledge of the size-dependent particle density, the determination of a size-resolved particle mass concentration is also possible.

3. Ford Design

It is a Constant Volume Sampling (CVS) tunnel based methodology. Incoming air flowrate is set at a constant value (250 m^3/h) and sampling of the particles takes place directly (partial volume) at the transport line which is vertical with respect to the ground. Filtered air is used for the dilution while a fully sealed chamber ensures a minimized background concentration. A multi-device-measurement approach is followed with the use of multiple probes.

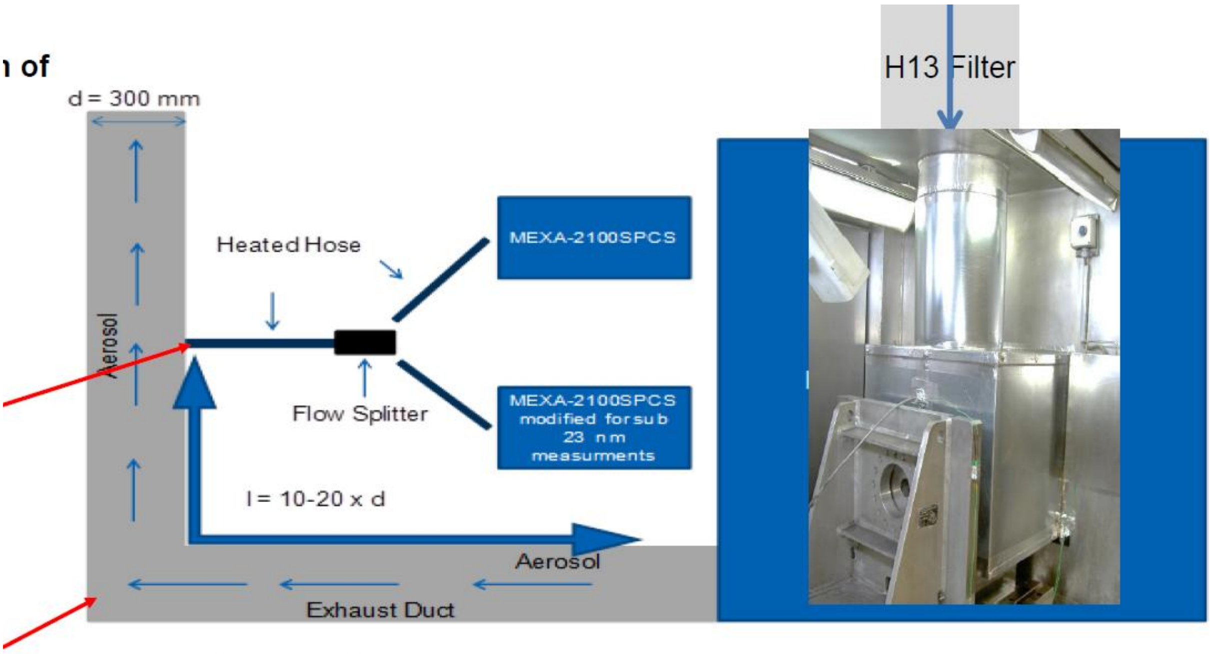


Losses in the chamber – and before the particles entrance in the duct – have not been studied, however, Ford's tests showed that not more than 2 sec are required for the chamber to be cleaned from generated particles 250 m^3/h. Inlet and outlet positions are optimized to achieve forced turbulent mixing while CFD confirms desired turbulent chamber flow. Background emissions in the chamber never exceed 1% of the overall emissions over a "normal" braking event, therefore they are not considered important.

Losses of smaller particles in the sampling tube are minimized for the selected air flow and duct diameter (diameter of 150 mm) as shown from CFD studies. The calculated residence time of the particles is no longer than 0.6 sec, therefore coagulation losses are minimized. Also, transport losses of bigger particles (2.0 µm – 20 µm) do not exceed 15% for selected samples. It is expected that the selected geometry results in minimized gravimetric losses for particles larger than 2 µm.

4. Horiba – Audi Design

It is a pseudo Constant Volume Sampling (CVS) tunnel with sampling at a 90-degree bend. It is not possible to measure volume of emitted brake dust pollution and only intake/exhaust air flow can be controlled with at least 5% accuracy. Incoming air flowrate can be adjusted (430 – 3500 m^3/h) and sampling of the particles for PN concentration and size distribution takes place directly (partial volume) at the transport line after the 90-degree bend. PM measurements can be conducted at the end of the horizontal part of the exhaust duct. Filtered air is introduced for the dilution while a fully sealed chamber ensures a minimized background concentration. The application of H13 filter will reduce background concentration and application of the chamber ensures 100% collection (transport and coagulation losses not considered) of emitted brake dust pollution. A multi-device-measurement approach can be followed. Temperature of heated line is 47°C and thus no volatile content will be removed. Like for exhaust case, heated line is applied only to prevent water condensation. Volatiles will be removed during measurements within SPCS and/or DMS, separately for each instrument.

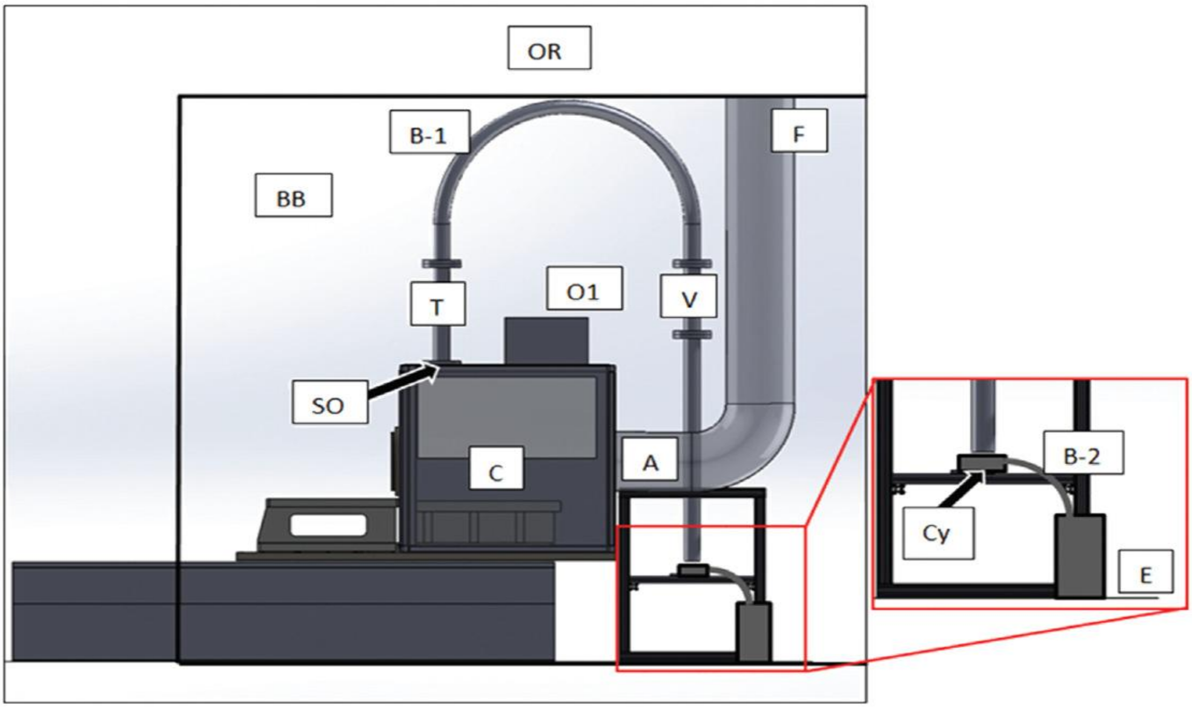


Optional sampling point for isokinetik particle mass measurements

PN measurement is strongly dependent on air flow rate. Also it was found that increasing air flow rate leads to reduction of residuals in brake dynamometer chamber and therefore lower residence time of the particles in the chamber. Overall, for tests measured with the optimum for the set-up inlet air velocity (3300 m^3/h), variation of PN was not found to be higher than ±20%. Similar PN variation was observed for all applied air flows, however, decreasing PN with decreasing air flow was noted. Particle emission was measured in the range of 10^5-10^8 particle/cm^3. The SPCS particle counter was modified according special requirements for brake particles emission measurements and provided fast response, high accuracy and reproducibility for measurements of brake dust emissions. Low measurement range was extended to 10 nm instead of 23 nm for exhaust measurements.

5. Brembo Design

It is a tunnel based methodology with sampling from a parallel flow. Incoming air flowrate can be adjusted (500 – 2500 m^3/h) and sampling of the particles for PN ad PM concentration and size distribution takes place directly (partial volume) at the end of the sampling line after the 180-degree bend through isokinetic nozzles. Filtered air is introduced for the dilution while a fully sealed chamber ensures a minimized background concentration. A multi-device-measurement (Dekati PM10 impactor, filter holder 47 mm, HT-ELPI+, TSI 3775 CPC) approach can be followed and a heated probe to remove the volatiles before the flow splitter is applied.



6. GM Design

Standard brake performance dyno arrangement. Dyno enclosure is optimized for brake performance testing and quick hardware changeover, not optimized for particulate measurement or including any particulate sampling equipment.

Table 1a. Uncertainties related to the technical specifications of the set-up

Technical Specifications	JARI	TU Ilmenau	Ford	Horiba – Audi	Brembo
Environmental conditioning of the incoming air	Controlled temperature at 20±5ºC and Relative Humidity lower than 35%	Controlled temperature and Relative Humidity of the incoming air	Controlled temperature and Relative Humidity of the incoming air	Controlled temperature and Relative Humidity of the incoming air	No conditioning of the incoming air. Monitoring of RH and temperature
Inlet air flowrate (Minimum – Maximum and Optimal Value)	Adjustable between 30 – 300 m^3/h with optimal value set mainly at 60 m^3/h	$PM_{2.5}$-setup: Optimal air flowrate value set at 850 m^3/h (Min: 100m^3/h – Max: 1000m^3/h)	Optimal air flowrate value set at 250 m^3/h	Adjustable between 430 – 3300 m^3/h with optimal value set at 3300 m^3/h	Adjustable between 500 – 2500 m^3/h with optimal value set at 1175 m^3/h
Duct diameter and geometry	Straight line CVS tunnel with a diameter of 84.9 mm (or 100 mm)	Horizontal π shaped duct with a diameter of 160 mm	Vertical reverse U shaped duct with a diameter of 150 mm	90-degree bend CVS tunnel with a diameter of 300 mm	Vertical reverse U shaped duct with a diameter of 56 mm
Air speed in main duct	Adjustable between 30 – 300 m^3/h with optimal value set at **2.9 m/s**	Adjustable – optimum: 12 m/s (850m^3/h)	3.9 m/s	Adjustable between 1.7 – 12.7 m/s with optimal value set at 12.7 m/s	Adjustable up to 14.4 m/s
Reynolds number in main duct	For 84.9 mm duct (80A) and air speed of 60 m^3/h: 16 (Re=6.6Vd)	$PM_{2.5}$-setup: 1.25e+5 (tunnel) 3.43e+4 (chamber)	39000	$3.4 \times 10^3 – 2.5 \times 10^5$	Re=12600
Shape of the brake enclosure	*	*	Circular shaped brake enclosure with small chamber volume: ~0.2 m^3	Optimized for minimum enclosure volume	Rectangular
Brake enclosure surface condition (i.e. electropolish)	*	*	Fully conductive chamber surface. No electrostatic particle losses expected.	Yes	*
Rotational direction and orientation of brake assembly relative to airflow	*	*	Inlet air flows towards the brake caliper at 45° from the lower vertical orientation; at caliper the disc rotation is opposite to the flow direction	Rotational direction is perpendicular to air flow. Top-to-Down cooling air approach	Dilution flow comes from the side of the disc (deviated by screens)

Type of flow in transport line (laminar, turbulent, etc.)	Laminar flow	Fully turbulent	Turbulent flow	Turbulent and/or pseudo-laminar	Well-developed flow
What is the setup capable of measuring?	PM$_{10}$, PM$_{2.5}$, PN Concentration and PN Distribution	PM$_{2.5}$, PN Concentration, PN Distribution PM$_{10}$-setup is available	PM$_{10}$, PM$_{2.5}$, PM$_{1.0}$ (Filter based). Real-time PM monitoring, PN, Particle size distributions from 0.005 – 20 µm	PM, PM distribution, PN concentration, PN distribution can be measured simultaneously	PM$_{10}$, PM$_{2.5}$, PN Concentration and PN and PM Distribution

Table 1b. Uncertainties related to the technical specifications of the set-up

Technical Specifications	LINK A	LINK B	LINK C	TU Ostrava	GM
Environmental conditioning of the incoming air	(20±5)°C; (50±10) %RH	(20±5)°C; (50±10) %RH	(20±5)°C; (50±10) %RH	Temperature controlled to (20±5)°C, temperature and humidity measured	(20±5)°C; (50±10) %RH
Inlet air flowrate (Minimum – Maximum and Optimal Value)	Adjustable between 250 – 2500 m^3/h. Optimal selected based on the duct dimensions and brake cooling rate	Adjustable between 250 – 2500 m^3/h. Optimal selected based on the duct dimensions and brake cooling rate	Adjustable between 250 – 2500 m^3/h. Optimal selected based on the duct dimensions and brake cooling rate	Max. 2500 m^3/h (@ 20°C; 101,325 kPa abs.). Flow measured and regulated	Adjustable between ~630 to 4900 m^3/h. **Not optimized for particulate sampling.**
Duct diameter and geometry	Straight line CVS tunnel with a diameter that can vary between 100 – 250 mm based on the flowrate and estimated losses	Vertical reverse U shaped duct with a diameter that can vary between 100 – 250 mm based on the flowrate and estimated losses	Vertical reverse π shaped duct with a diameter that can vary between 100 – 250 mm based on the flowrate and estimated losses	"C"-shaped duct with brake chamber at the bottom. Approx. 4 m long, 300 mm diameter circular cross-section tunnel with isokinetic sampling point.	Square 356 x 356mm inlet and outlet duct. **Not optimized for particulate sampling.**
Air speed in main duct	150-mm duct: 4 m/s (at 250 m^3/h) - 40 m/s (at 2500 m^3/h). 250-mm duct: 1.4 m/s (at 250 m^3/h) - 14 m/s (at 2500 m^3/h)	150-mm duct: 4 m/s (at 250 m^3/h) - 40 m/s (at 2500 m^3/h). 250-mm duct: 1.4 m/s (at 250 m^3/h) - 14 m/s (at 2500 m^3/h)	150-mm duct: 4 m/s (at 250 m^3/h) - 40 m/s (at 2500 m^3/h). 250-mm duct: 1.4 m/s (at 250 m^3/h) - 14 m/s (at 2500 m^3/h)	315 mm duct: Approx. 8.91 m/s (at 2500 m^3/h)	1.4 to 10.8 m/s

Reynolds number in main duct	For 150-mm duct: 38K to 383K For 250-mm duct: 23K to 230K	For 150-mm duct: 38K to 383K For 250-mm duct: 23K to 230K	For 150-mm duct: 38K to 383K For 250-mm duct: 23K to 230K	For 315-mm duct 180K	37K to 284K
Shape of the brake enclosure	Round with 15° transition to main duct	Round with 15° transition to main duct	Round with 15° transition to main duct	Rectangular closed box (L:1100mm x H: 910mm x W: 500mm)	Rectangular, closed box. 1180mm width x 560mm depth x 915mm height.
Brake enclosure surface condition (i.e. electropolish)	Stainless steel with internal electropolish	Stainless steel with internal electropolish	Stainless steel with internal electropolish	Stainless steel (no polish or special treatment)	Painted steel (no polish or special treatment)
Rotational direction and orientation of brake assembly relative to airflow	Providing same air rotation relative to main airflow	Providing same air rotation relative to main airflow	Providing same air rotation relative to main airflow	Providing same air rotation relative to main airflow	Can be adjusted either way
Type of flow in transport line (laminar, turbulent, etc.)	Turbulent on transport line, laminar on sampling lines	Turbulent on transport line, laminar on sampling lines	Turbulent on transport line, laminar on sampling lines	Turbulent	Turbulent
What is the setup capable of measuring?	PN, PM, size distribution from 6 nm to 20 µm. Measurement also includes gravimetric sampling in two independent instruments.			PN, PM, Size Distributions. Multiple sampling locations close to the brake assembly (non-isokinetic) and in the tunnel (isokinetic), possibility to use additional instruments and samplers.	Currently not for PM-PN measurement – measures brake performance metrics (torque, pressure, temperature, etc.)

Table 2a. Uncertainties related to other parameters

Parameters related to uncertainties	JARI	TU Ilmenau	Ford	Horiba – Audi	Brembo
Background level concentration (Please add any measurement or estimation)	Use of activated carbon and HEPA filters to minimize the background effect	Use of HEPA filters and fully sealed chamber to minimize the background effect	Use of HEPA filters and fully enclosed chamber minimize the background effect (less than 1% of total emissions)	Use of activated carbon and HEPA filters to minimize the background effect	Use of HEPA filters and fully sealed chamber minimize the background effect (PN background [] 100-200 cm^{-3})
Estimated setup leakage flow (e.g. in m^3/h, air-tightness test) and estimated impact of leakages in the setup (impact to the measurement by i.e. increase background)	Still to be estimated	Still to be estimated	A rough bad case estimation of < 9 m^3/h (which is based on a particle measurement approach and the resulting leakage flow is the resolution limit of the device). In any case, since the measurement chamber is surrounded by pre-filtered air (DT reading: 0 µg/m^3) we do not expect any contamination from leakages. Brake particles cannot escape since the setup works with negative pressure	Still to be estimated	Still to be estimated
Measurement of inlet air flow-rate (Errors due to not accurate measurement of inlet air-flow rate) HOW is it done? Is the flow continuously controlled? Are inlet and exhaust duct air flow rates the same or is there a difference?	Ahead of HEPA Filter with mass flow meter	Differential pressure sensor	Stationary, continuous flow measurement (vortex flow principle based). Blower is feedback controlled by flow measurement	Continuous measurement with Pitot tube	Inlet air flow-rate is continuously monitored (additional Venturi in the parallel U-shaped sampling line)
Position of air speed/flow measurement, relative to sampling position, and to the last duct disturbance (bends, constriction, etc.). Please provide the actual	Behind Sampling position with mass flow meter	0.25 m behind sampling position / 0.75m behind bend	Behind sampling position and in front of the blower; in front of the sensor a honeycomb flow-straightener is placed; flow-straightener and sensor combination is calibrated in an	Behind sampling position using continuous measurement with Pitot tube and/or ultrasonic flow meter with 5% error	Venturi placed 50 cm from the sampling point without duct disturbance

location			external wind tunnel		
Sealing method between chamber and environment and to dyno driveshaft			Rotary shaft seal. Additional sealing tapes between chamber parts and environment	Yes	Rubber seal, Dyno driveshaft not sealed (considered as an extra excess, not important due to flow measurement in parallel U-shaped sampling line)
Residence time in the chamber (CFD studies or/and in-situ measurement of concentration levels) METHOD	No measurement or CFD simulation available yet	CFD studies show a very fast evacuation of the chamber (< 3s)	CFD studies show very fast evacuation of the chamber close to 3s	Direct air flow leads almost all ultrafine particles to the duct. CFD is ongoing project	CFD studies show a very fast evacuation of the chamber (< 3s)
Inhomogeneous aerosol concentration (Small distance after last bend – EPA Method 1A of 8D)	Not the case due to long enough CVS tunnel	CFD models show a particle uniformity of 80% for speeds <30 km/h which increases up to 90% for 60-150 km/h	Homogeneous particle concentration across duct confirmed by measurements	Not the case due to long enough CVS tunnel (At least 10 – 20 diameters long)	No bends before the coaxial sampling
Residence time of particles in the duct/tunnel	Probably high – estimated between 15 and 25 s	Low – Penetration of particles calculated > 90%	Low – CFD studies show high particles velocity in the tube (4-5 m/s)	Not the case since length of tunnel is too short (L≈4 m) in respect to air speed (12.7m/s). Mainly defined by residence time of instruments	Very low – Does not exceed 2 seconds
Tubing material and finish (stainless steel; grounded; electropolished)	Fully conductive chamber surface and sampling tunnel. Electropolished sampling tube for instruments	Stainless steel	Fully conductive chamber surface. No electrostatic particle losses expected.	Electropolished chamber surface and sampling tunnel. Electropolished sampling tube for instruments	Fully conductive chamber surface. Stainless steel chamber and tubing. Grounded
Difficulty in cleaning the set-up (Rate from Very Difficult + to Very Easy +++++)	+++ (Approximately half day)	++++	++++ (Chamber consists of several parts. All chamber parts and transport lines can be dismounted and accessed)	++++ (Up to 4 hours, depends on housing design)	+++ (4-6 hours are necessary to disassemble the chamber, clean it and assemble back)
Time/effort for brake inspection/change (of disc and pads)?			Brake inspection: 15 min; Change of disc and pads: 2h due to inspection opening at	Depends on housing design	Relatively easy due to possibility to open only one panel of the chamber to reach

			chamber		the brake assembly
Particle measurement system – size range for dynamic range	• FMPS: 5.6-560 nm • CPC: 1-10k #/cm^3 • APS: 0.37-20 µm • (OPS: 0.30-10 µm) • LPI (LP-20) : 0.06-12 µm • (NanoMOUDI: 0.01-10 µm) • MCI Impactor PM$_{10}$ & PM$_{2.5}$	• Horiba SPCS (10nm-2.5 µm) • TSI3776 (2.5nm->3 µm) • Cambustion DMS500 (5nm-2.5 µm) • Dekati ELPI+ (6nm-10 µm) • AVL PN-PEMS (-) • TSI Dust Trak (PM$_{2.5}$, PM$_{10}$) • Impactor PM$_{10}$, PM$_{2.5}$ • PM$_{10}$- 45mm filter	• APS: 0.37-20 µm • OPS: 0.30-10 µm • ELPI : 0.006-10 µm • EEPS: 0.005-0.5 µm • DT: >0.3µm • Impactor: PM$_{10}$, PM$_{2.5}$ & PM$_{1.0}$	• SPCS: 0-1x10^8 #/cm^3 • EEPS: 5,6-560nm • DMS: 5nm-1 µm • ELPI: 6nm-10 µm • MDLT, DLS: Total PM measured on filter	• HT-ELPI+: 6 nm to 10 µm (500 to 1e7 cm^{-3}) • CPC: 1-1e7 cm^{-3} • Impactor PM$_{10,}$ PM$_{2.5,}$ PM$_1$ • PM$_{10}$ 47mm filter

Table 2b. Uncertainties related to other parameters

Parameters related to uncertainties	LINK A	LINK B	LINK C	TU Ostrava	GM
Background level concentration (Please add any measurement or estimation)	Use of filtered air (HEPA + activated carbon) to minimize the background effect (less than 20% of testing levels or better)	Use of filtered air (HEPA + activated carbon) to minimize the background effect (less than 20% of testing levels or better)	Use of filtered air (HEPA + activated carbon) to minimize the background effect (less than 20% of testing levels or better)	Varies due to limited efficiency of bag filters. Typically several '000s particles per cm^3	Not available
Estimated setup leakage flow (e.g. in m^3/h, air-tightness test) and estimated impact of leakages in the setup (impact to the measurement by i.e. increase background)	No actual measurements available. All incoming air filtered. Dyno setup design includes standard fixture size to ensure sealing at interface with enclosure walls. Positive pressure to avoid entry of external non-filtered air	No actual measurements available. All incoming air filtered. Dyno setup design includes standard fixture size to ensure sealing at interface with enclosure walls. Positive pressure to avoid entry of external non-filtered air	No actual measurements available. All incoming air filtered. Dyno setup design includes standard fixture size to ensure sealing at interface with enclosure walls. Positive pressure to avoid entry of external non-filtered air	Negligible relative to background due to limited efficiency filtration.	Not available
Measurement of inlet air flow-rate (Errors due to not accurate measurement of inlet air-flow rate) HOW is it done? Is the flow continuously controlled? Are inlet	Continuous measurement with std Pitot tube. Closed system with same duct shape and dimensions prior and post	Continuous measurement with std Pitot tube. Closed system with same duct shape and dimensions prior and post	Continuous measurement with std Pitot tube. Closed system with same duct shape and dimensions prior and post	Measuring orifice in a technical room downstream of the tunnel and all sampling locations, calibrated to the	Continuous measurement with anemometer

and exhaust duct air flow rates the same or is there a difference?	enclosure	enclosure	enclosure	actual geometry of the system	
Position of air speed measurement, relative to sampling position, and to the last duct disturbance (bends, constriction, etc.). Please provide the actual location	Behind sampling position per EPA method 1A, 8 diameters after last bend and 2 diameters before next bend	Behind sampling position per EPA method 1A, 8 diameters after last bend and 2 diameters before next bend	Behind sampling position per EPA method 1A, 8 diameters after last bend and 2 diameters before next bend	Measuring orifice in a technical room downstream of the tunnel and all sampling locations, calibrated to the actual geometry of the system	Anemometer upstream of brake assembly in inlet duct. 90 degree bend from inlet duct (vertical) to brake enclosure (horizontal).
Sealing method between chamber and environment and to dyno driveshaft	Sealing to ensure air-tightness while minimizing torque losses due to friction on drive side	Sealing to ensure air-tightness while minimizing torque losses due to friction on drive side	Sealing to ensure air-tightness while minimizing torque losses due to friction on drive side	Standard performance dyno enclosure with rubber seals against steel surface. Sealing to ensure air-tightness while minimizing torque losses due to friction on drive side	Standard performance dyno enclosure not optimized for PM measurement (rubber seals against steel surface)
Residence time in the chamber (CFD studies or/and in-situ measurement of concentration levels) METHOD	No measurements available yet. Estimated in less than 5 s	No measurements available yet. Estimated in less than 5 s	No measurements available yet. Estimated in less than 5 s	Not evaluated	Not available
Inhomogeneous aerosol concentration (Small distance after last bend – EPA Method 1A of 8D)	Not the case due to long enough duct based on the EPA Method 1A of 8D	Not the case due to long enough duct based on the EPA Method 1A of 8D	Not the case due to long enough duct based on the EPA Method 1A of 8D	> 10 diameters from last bend	Not available
Residence time of particles in the duct/tunnel	Depend on the selected flowrate. Highest flowrates come with low residence time. less than 1 s at typical air speed for (250 to 1000) m³/h	Depend on the selected flowrate. Highest flowrates come with low residence time. less than 2 s at typical air speed for (250 to 1000) m³/h	Depend on the selected flowrate. Highest flowrates come with low residence time. less than 1.5 s at typical air speed for (250 to 1000) m³/h	Less than 1 s	Not available.
Tubing material and finish (stainless steel; grounded; electropolished)	Stainless steel duct and brake enclosure with electropolish in the wet area	Stainless steel duct and brake enclosure with electropolish in the wet area	Stainless steel duct and brake enclosure with electropolish in the wet area	Steel duct with galvanized zinc surface and stainless steel brake enclosure without any polish.	Stainless steel without electropolish

Difficulty in cleaning the set-up – Would cause possible contamination (Rate from Very Difficult + to Very Easy +++++)	+++++	++	+++	++++	Very difficult (+)
Time/effort for brake inspection/change (of disc and pads)?	Within standard changeover times of less than 30 min. Fixture change would be within 1h	Within standard changeover times of less than 30 min. Fixture change would be within 1h	Within standard changeover times of less than 30 min. Fixture change would be within 1h	Within standard changeover times of less than 30 min. Fixture change would be within 1h. Inspection windows and digital camera for on-line view.	30 minutes max (very simple)
Particle measurement system – size range for dynamic range (Instrumentation)	• EEPS: 5.6-560 nm • CPC: 1-10k $\#/cm^3$ • APS: 0.37-20 µm • QCM M140: 0.045-2.5 µm • MOUDI Impactor for PM_{10}	• EEPS: 5.6-560 nm • CPC: 1-10k $\#/cm^3$ • APS: 0.37-20 µm • QCM M140: 0.045-2.5 µm • MOUDI Impactor for PM_{10}	• EEPS: 5.6-560 nm • CPC: 1-10k $\#/cm^3$ • APS: 0.37-20 µm • QCM M140: 0.045-2.5 µm • MOUDI Impactor for PM_{10}	• 2 x EEPS: 5.6-560 nm • 2 x ELPI: 10 nm – 10 um aerodynamic diameter • DLPI: 10 nm – 10 um • CPC: 0.1-100k $\#/cm^3$ • APS: 0.37-20 µm • Ejector diluters: 8:1, 40:1, 100:1, 1000:1 • Rotating disc diluter dynamically adjustable dilution ratio 15:1-3000:1	Not available

Table 3a. Uncertainties related to losses

Related Losses	JARI	TU Ilmenau	Ford	Horiba – Audi	Brembo
Sampling losses due to anisokinetic extraction of the aerosol at the sampling location (affects mainly the size distribution of larger particles)	Isokinetic sampling – Probe geometry according to air and tube velocity	Isokinetic sampling / Constant velocity sampling (specific probe diameter)	Isokinetic sampling – Probe geometry according to air and tube velocity	Isokinetic sampling – Probe geometry according to air and tube velocity	Not fully laminar but well developed flow – Probe geometry according to air and tube velocity
Sampling losses due to anisoaxial extraction of the aerosol at the sampling location	Not the case due to horizontal set-up	Probe faces straight into the air direction (no inclination)	Not the case due to vertical set-up		Not the case due to vertical set-up
Losses due to not positioning sampling probes at the correct point with respect to the flow (laminar flow + homogenous flow)	Most probably not the case due to low inlet air flow rate and long residence time of particles in the CVS tunnel	CFD study shows central positioning of the probe as optimum	CFD study shows slightly different flow velocities at the position of the probe		Flow not fully laminar therefore some losses could occur. Still to be checked
Coagulation/agglomeration (Distance from sampling point + residence time could affect both PN concentration and distribution when > 10^7 #/cm^3). Further definition of 2-3 typical CMD and GSD, and transport times to instrument (enclosure + duct + and sampling line) to provide comparable results	Could be significant due to long residence time of the particles in the tunnel in case of high concentrations for PN	Probably not taking place due to low residence time	Probably not taking place due to low residence time of about 0.6 sec	May take place depending on the air-flow rate. Low air-flow rates result in high residence time increasing losses	Probably not taking place due to very low residence time in the duct
Condensation transformation (Occurs under supersaturation conditions and affects PN distribution)	We should discuss if these phenomena occur with the low presence of volatiles	We should discuss if these phenomena occur with the low presence of volatiles	We should discuss if these phenomena occur with the low presence of volatiles	We should discuss if these phenomena occur with the low presence of volatiles	We should discuss if these phenomena occur with the low presence of volatiles
Adsorption (Occurs at pressures below saturation – affects mainly PN distribution as well as PM measurements)	We should discuss if these phenomena occur with the low presence of volatiles	We should discuss if these phenomena occur with the low presence of volatiles	We should discuss if these phenomena occur with the low presence of volatiles	We should discuss if these phenomena occur with the low presence of volatiles	We should discuss if these phenomena occur with the low presence of volatiles

Nucleation transformation (Occurs only at high saturation ratios – affects PN and PM measurement when no catalytic stripper is applied)	Most probably takes place at high temperature. This is the case also in real world	Most probably takes place at high temperature. This is the case also in real world	Most probably takes place at high temperature. This is the case also in real world	Most probably takes place at high temperature. This is the case also in real world	Most probably takes place at high temperature. This is the case also in real world
Thermophoretic losses (This is mainly due to high temperature difference between the tubes and the flow)	Most probably not relevant	Most probably not relevant	Most probably not relevant	Most probably not relevant	Most probably not relevant
Gravitational/Inertial losses (arise from the inability of particles to follow fluid streamlines due to their inertia – relevant mainly for bigger particles)	Possible. Used DustTrak II 8530 corrected by gravimetric measurement	Compliance with the above mentioned concept for the analysis of transport efficiency. Measurements revealed a efficiency of 85% over all emitted particle sizes (mass)	Devices are placed below sampling point to avoid gravitational loss. Transport losses of particles <10 µm do not exceed 5%	Current set-up suitable for PN measurements. Could apply PM measurement before the 90^0 angle with isokinetic sampling	Devices are placed below sampling point to avoid gravitational loss. Also flow is adjusted for PM measurements
Diffusion losses (relevant for particles < 50 nm and is much faster in highly turbulent flows – depends on the residence time)	Could be significant due to long residence time of the particles in the tunnel	Exist for particles smaller than 10 nm but in any case not higher than 15%	Diffusional losses estimated to be smaller than 0.5 % for particles down to 10 nm		Could be significant due to turbulent flow before the Venturi. There will be an estimation on this

Table 3b. Uncertainties related to losses

Related Losses	LINK A	LINK B	LINK C	TU Ostrava	GM
Sampling losses due to anisokinetic extraction of the aerosol at the sampling location (affects mainly the size distribution of larger particles)	Isokinetic sampling – Probe geometry according to air and tube velocity. Sampling airflow between 4 – 40 L/min based on the incoming air flowrate. Actual settings will be a function of final duct size and instrument flow rate	Isokinetic sampling – Probe geometry according to air and tube velocity. Sampling airflow between 4 – 40 L/min based on the incoming air flowrate. Actual settings will be a function of final duct size and instrument flow rate	Isokinetic sampling – Probe geometry according to air and tube velocity. Sampling airflow between 4 – 40 L/min based on the incoming air flowrate. Actual settings will be a function of final duct size and instrument flow rate	N/A - Isokinetic sampling	Not available

Sampling losses due to anisoaxial extraction of the aerosol at the sampling location	Not the case due to axial alignment between duct and sampling tube	Not the case due to axial alignment between duct and sampling tube	Not the case due to axial alignment between duct and sampling tube	N/A - Isokinetic sampling	Not available
Losses due to not positioning sampling probes at the correct point with respect to the flow (laminar flow + homogenous flow)	Pending to confirm positioning based on air speed measurements per ISO and EPA methods	Pending to confirm positioning based on air speed measurements per ISO and EPA methods	Pending to confirm positioning based on air speed measurements per ISO and EPA methods	Not evaluated	Not available
Coagulation/agglomeration (Distance from sampling point + residence time could affect both PN concentration and distribution when $> 10^7$ #/cm^3). Further definition of 2-3 typical CMD and GSD, and transport times to instrument (enclosure + duct + and sampling line) to provide comparable results	Depends on the residence time of the particles in the duct. Probably air flowrate is adjusted to minimize losses. Pending	Depends on the residence time of the particles in the duct. Probably air flowrate is adjusted to minimize losses. Pending	Depends on the residence time of the particles in the duct. Probably air flowrate is adjusted to minimize losses. Pending	So far, no clear / significant occurrence observed (evaluated by simultaneous sampling close to the brake assembly and in the tunnel)	Not available
Condensation transformation (Occurs under supersaturation conditions and affects PN distribution)	We should discuss if these phenomena occur with the low presence of volatiles	We should discuss if these phenomena occur with the low presence of volatiles	We should discuss if these phenomena occur with the low presence of volatiles	So far, no clear / significant occurrence observed (by simultaneous sampling close to the brake assembly and in the tunnel)	We should discuss if these phenomena occur with the low presence of volatiles
Adsorption (Occurs at pressures below saturation – affects mainly PN distribution as well as PM measurements)	We should discuss if these phenomena occur with the low presence of volatiles	We should discuss if these phenomena occur with the low presence of volatiles	We should discuss if these phenomena occur with the low presence of volatiles	So far, no clear / significant occurrence observed (by simultaneous sampling close to the brake assembly and in the tunnel)	We should discuss if these phenomena occur with the low presence of volatiles
Nucleation transformation (Occurs only at high saturation ratios – affects PN and PM measurement when no catalytic stripper is applied)	Most probably takes place at high temperature. This is the case also in real world	Most probably takes place at high temperature. This is the case also in real world	Most probably takes place at high temperature. This is the case also in real world	So far, no clear / significant occurrence observed (by simultaneous sampling close to the brake assembly and in the tunnel)	Most probably takes place at high temperature. This is the case also in real world

Thermophoretic losses (This is mainly due to high temperature difference between the tubes and the flow)	Most probably not relevant	Most probably not relevant	Most probably not relevant	Not evaluated, not expected due to small temperature differences	Most probably not relevant
Gravitational/Inertial losses (arise from the inability of particles to follow fluid streamlines due to their inertia – relevant mainly for bigger particles)	Minimized for given inlet air flowrate and duct diameter. Needs quantification or estimation at design level and further validation with reference aerosols	Minimized for given inlet air flowrate and duct diameter. Needs quantification or estimation at design level and further validation with reference aerosols	Minimized for given inlet air flowrate and duct diameter. Needs quantification or estimation at design level and further validation with reference aerosols	Evaluated by full mass balance (loss of material vs. sum of material deposited within the chamber and accounted for in emissions)	Not available
Diffusion losses (relevant for particles < 50 nm and is much faster in highly turbulent flows – depends on the residence time)	transport times of less than 5 s	Longer particle transport may affect particles smaller than 10 nm. A study on this is pending	Intermediate residence time of particles may affect particles smaller than 10 nm. A study on this is pending	Not expected to be significant (transport time within 1 s)	Not available