Supplier Scouting Opportunity Synopsis 2023-042

Item to be scouted: Photoacoustic Aerosol Black Carbon Mass Analyzer

Days: 30

Item description: U.S. EPA regulations require the measurement of vehicle exhaust particulate matter (PM) mass emissions due to its impacts on human health determined from health effects studies and documented in the National Ambient Air Quality Standards (NAAQS). Design of sampling systems and measurement techniques used to measure PM in vehicle exhaust emissions requires special consideration due to the chemical complexity of PM. PM in exhaust emissions are not stable and can change due to other volatile and semivolatile gaseous material in the gaseous sample stream.

At the U.S. EPA's National Vehicle and Fuel Emissions Laboratory (NVFEL), an initiative has been started to understand the complexities of measuring particle number, size and other characteristics in a combustion engine emissions sample train. An additional diagnostic instrument that allows for measurement of PM mass is a photoacoustic black carbon (BC) mass analyzer.
This is a procurement to acquire a photoacoustic BC mass analyzer for use at the EPA's National Vehicle and Fuel Emissions Laboratory (NVFEL).

NAICS code: 334516

Technical Information

Supplier Information

Type of supplier being sought: Manufacturer
Reason for scouting submission: 2nd supplier

Summary of technical specifications and performance requirements
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Describe the manufacturing processes (elaborate to provide as much detail as possible): Electronic and mechanical assembly

Provide dimensions / size / tolerances / performance specifications for the item:

1) Ability to measure PM BC mass concentration:

a. If not otherwise stated, photoacoustic analyzers shall meet the requirements of 40 CFR Part 1065 and 1066. (If there are any conflicting requirements between the CFR parts, or any part of this SOW, the requirement with greater stringency will apply.)
b. Zero and span drift shall each be less than ± 1% full scale reading over 4 hours.
c. must be range configurable for 0.001 mg/m3 to 150 mg/m3 with instrument limit of detection at or below 0.001 mg/m3
d. analyzer must be accurate to ≤1% of full scale reading
e. analyzer must be repeatable to ≤1% of full scale reading
f. analyzers must have noise ≤1% of full scale reading

g. Linearity verification (e.g., 40 CFR 1065.307) using a BC source
h. Sample flow range up to at least 0.005 m3/minute
i. Data logging frequency of at least 10 hertz
j. Temporal resolution : T90 < 2 seconds
k. The delivered system will not update any calibration parameters without operator input.
l. All alarm or warning messages will be clearly described in the provided documentation.
m. In-production instrument data illustrating the in-production instrument's ability to meet each of the specifications listed above shall be provided by the contractor in the proposal
2) User interface/data control and acquisition software and hardware:
a. Hardware
i. Ethernet communication port for instrument control, data transfer and compatibility with NVFEL test cells communication protocols
ii. Front panel user display with appropriately labeled control knobs, buttons, and/or switches
iii. Panels with appropriately labeled input gas and sample connectors
b. Software
i. Able to monitor and log multiple instrument operation parameters, but not limited to, raw sample and dilution gas flows, mass concentration, sample gas temperatures and pressures
ii. Compatible with Microsoft Windows 10
iii. Data output to standardized, non-proprietary file format nonspecific to a particular software application (e.g., ASCII or text file format with standard delimiters that do not contain specialized formatting characters)
3) Minimal ambient conditions operational range
a. temperature range : 0°C through 30°C
b. pressure range : 0.95 to 1.05 bar
4) Dual power (500 watts maximum):
a. 120 volt AC, 60Hz, 2 amp
b. 24 volt DC, 20 amp
5) Wheeled cart for analyzer for portability
6) Sample lines
a. Heated 6 meter
b. Heated 3 meter
c. Unheated 2 meter
7) 3 Sample probes compatible for use in vehicle and engine dynamometer constant volumes sampling (CVS) systems
8) Minimal impact on facility resources in terms of safety considerations (electrical connections insulated and covered, safety switches, guards for rotating parts, …). All safety considerations and mitigation will be explained in writing in the proposal.

List required materials needed to make the product, including materials of product components: See attached

Are there applicable certification requirements?: See dimensions/size/tolerances/performance specifications.

Are there applicable regulations?: No
Are there any other standards, requirements, etc.?: No

Business Information

Volume and pricing

Estimated potential business volume: 1 unit

Estimated target price / unit cost information (if unavailable explain): $150,000

Delivery requirements

When is it needed by?: 3 months

Describe packaging requirements: this is a delicate scientific instrument as should be packed accordingly to avoid any damage during shipping (there are no hazardous materials)

Where will this item be shipped?:
EPA NVFEL
2565 Plymouth Road
Ann Arbor, MI 48105

Application Guide

AVL Micro Soot Sensor 2 (MSS2)

AVL MSS2 Application Guide Revision 1 (preliminary)

Contents

1. Introduction

The AVL Micro Soot Sensor 2 (MSS2) is a particle measurement instrument dedicated to soot. It is designed to deliver a continuous (time-resolved) signal of the soot concentration. It is based on the photoacoustic principle. An exhaust conditioning system as well as a dilution air compressor are integrated into the device. It allows the use of a constant dilution at dilution ratios ranging from 2 to 20. For details about the working principle and the internal design of the instrument please check out the MSS2 product guide.

This document covers an overview about application related topics. It provides additional information and does not repeat topics, which are already part of the product guide. Maintenance and operation of the instrument are not within the scope of this document, these topics are discussed in the MSS2 product guide in detail. To make best use of this guide it is mandatory to read the product guide first.

The MSS2 is the next generation device following the MSSplus and inherits many features from the latter. The design has been improved to address a wider range of applications. The device is more versatile and better suited for the use on board a vehicle.

2. The AVL Micro Soot Sensor 2

2.1. Calibration

An accepted international standard for soot does not exist. Thus, the definition of accuracy for a soot measuring instrument and the definition of an accepted calibration method is difficult. The photoacoustic sensor of the Micro Soot Sensor is calibrated against combustion soot emitted by a CAST (“Combustion Aerosol Standard”). This instrument produces an exhaust flow with a soot concentration that is stable to better than 5% and with a marginal volatile fraction. The exhaust is diluted in a mixing chamber. The diluted exhaust is fed to the Micro Soot Sensor as well as to a semi-continuous OC/EC analyzer which serves as the calibration reference. The OC/EC analyzer determines the content of elemental carbon by a pyrolytic measurement following an optimized temperature protocol derived from the NIOSH 5040 method (NIOSH Handbook of analytical Methods). The used CAST aerosol consists of >95% black elemental carbon (BC). In addition to this procedure a gravimetric measurement versus a loaded TX40 filter is conducted as an additional quality check. Filter weighing and conditioning is carried out in accordance to ISO16183 (7.1.3).

2.2. Drift Compensation

The sensitivity of the Micro Soot Sensor signal shows a certain amount of drift over lifetime. This is usually caused by the ageing of the microphone but hardly ever by a drift in laser beam intensity. Since a span check with calibration gases doesn’t work with aerosol measurement instruments, a span check with a so-called “absorber window” has been developed. This span check should be performed at least once a week, depending on use. The (automatic) adjustment of the calibration factor should be carried out if the error in absorber window reading (compared to its factory set value) exceeds 5%.

The absorber window consists of an aluminium plate with a black coating, which is mounted on a special “entrance window” for the laser. In the “span check” function the produced signal is measured. The absorber does not simulate soot, it just generates a signal produced by a certain laser power with a certain microphone sensitivity. If the laser power or the microphone sensitivity changes, then the signal from the absorber window will change as well. Since both, the real soot signal and the signal from the absorber window change linearly with laser power and microphone sensitivity, the signal change of both will be proportional. For instructions on this procedure please read the instructions in the MSS2 product guide (chapter 5.7.2).

The reference value for the attached absorber window is determined during factory calibration and should not be changed by the operator.

If the calibration factor reaches an upper limit, which corresponds approximately to a 300% change in sensitivity, then the instrument must be refurbished with new microphones (or a new laser in very few cases). For this kind of repair, the device needs to be sent to AVL.

An additional method to characterize the long-term drift is the check of the peak intensity during the resonance scan (MSS2 product guide, chapter 5.7.2). The peak intensity (in mV) upon delivery is recorded in the end test protocol, and a sensitivity drift can be deduced from the change in this peak intensity. Please note that the value may show a day-to-day variation by +/-10%.

A zero drift can occur in the Micro Soot Sensor due to particle deposition on the windows and in the inner glass tube. The zero drift is not connected to the calibration factor. It would add a constant bias to the measured values if it was not continuously monitored and adjusted. A zero check and compensation of the bias is carried out automatically whenever the system is set into STANDBY.

2.3. Dilution Accuracy

The MSS2 dilution system produces a certain amount of dilution error, which depends on the dilution ratio. For the MSSplus the maximum acceptable error for a given dilution ratio was specified by using equation 1 (see MSSplus product guide, technical specifications).

$$\text{Error [\%]} = 2 + (0.5 * DR) \text{ with } DR = \text{Dilution Ratio} \qquad [1]$$

Although the MSS2 dilution system has been re-designed (the MFM was replaced by a set of critical flow orifices), the accuracy can be expected to be comparable. For a dilution ratio of DR=3 the error would be 3%, for DR=10 it would be 7%, or 12% for DR=20 respectively.

The reference method for checking the dilution accuracy is a differential flow check against an external reference flow meter. This check is common for partial flow dilution systems and is described in several technical regulations (e.g. ISO16183). If no reference flow meter is available, the setup from chapter 2.4, case 2 can be used for a quick dilution check. Varying the dilution ratio between DR=2 and DR=10 (stable engine operation!) should yield in a constant value for the sample soot concentration. Higher dilution ratios may introduce a slight drift as well as a higher noise level.

2.4. Guideline for comparing MSS Devices on Exhaust

If the comparability between different individual Micro Soot Sensors shall be checked in order to minimize the deviation, there are some relatively simple approaches to achieve this goal by using engine exhaust.

The test setup must be optimized in a way to minimize artifacts as much as possible. Only when influences from the sampling setup can be excluded, it is possible to determine the real deviation originating from the devices. This is more difficult with any particle measurement instrument than it usually is for gas analyzers. With the recommendations given in the examples below, it will be possible to obtain a good result.

Case 1: Comparing two Sensor units

This approach can be used to determine the deviation between individual sensor units by eliminating the error introduced by dilution. This can be any combination of MSS, MSSplus or MSS2. It can also be used to minimize the deviations between measurements taken with different devices. Note that this does not improve the absolute measurement accuracy, nor does it replace a factory calibration, but it will help to reduce the scatter between the devices.

A schematic drawing of the setup can be found in figure 1. For the sample lines we recommend using either conductive tubing or the yellow Tygon hoses provided with the instrument (available from AVL, SS0444).

Step by step procedure:

1) Select one device as the reference. This is ideally an instrument with a fresh calibration.
2) Connect the dilution cell with a probe in a piece of straight pipe in the exhaust stack of a combustion engine (diesel engine preferred due to high soot level and low humidity, no DPF) in a backpressure-free area, ideally tailpipe.
3) Connect the outlet of the cell to a buffer volume of ~100-150ml (steel, available from AVL) via a piece of tubing (~50cm)
4) Connect the buffer with a Y-piece (steel or antistatic plastic, no T-piece!) by using a hose of min.100cm length. This is important to obtain good mixing at the split.
5) The sample ports of two instruments (reference and candidate) must be connected to the ends of the Y-piece with two hoses of approximately equal length (~50-100cm)
6) Connect the dilution air outlets of both conditioning units with the air inlet of the single dilution cell by using another Y-piece.
7) Now warm up the engine and select a steady state point with stable soot emissions. The soot level can be anywhere within the range of detection. **No transient operation!**
8) Select the same dilution ratio on both instruments (between 3 and 10 is best). Start the measurement. The readings of both instruments can be compared directly. The sensor concentration of soot should be somewhere between 1 and 10 mg/m³ for this exercise.
9) Swap out the sample positions to exclude sampling artifacts originating from the setup. The deviation should stay the same for each device, no matter which branch of the Y-splitter the devices are sampling from.

10) If desired, adjust the calibration factor of the candidate until the deviation between the instruments is as close to zero as possible. For details see MSS2 product guide, chapter 5.6.4.2.

The MSS2 by default operates with a higher sample flow (~7.9 l/min) than the MSS. Whenever using a Y-splitter, the flow in both branches should be equal to avoid sampling artifacts. For the comparison between an MSS2 and an MSS it is highly recommended to switch the MSS2 to the low flow setting (~3.9 l/min). This option is available in the DUI (Checkbox “Sample Flow low” located in section “Parameters” of the DUI). If the MSS2 shall be operated at the default flow setting, the method described below (case 2) is preferred.

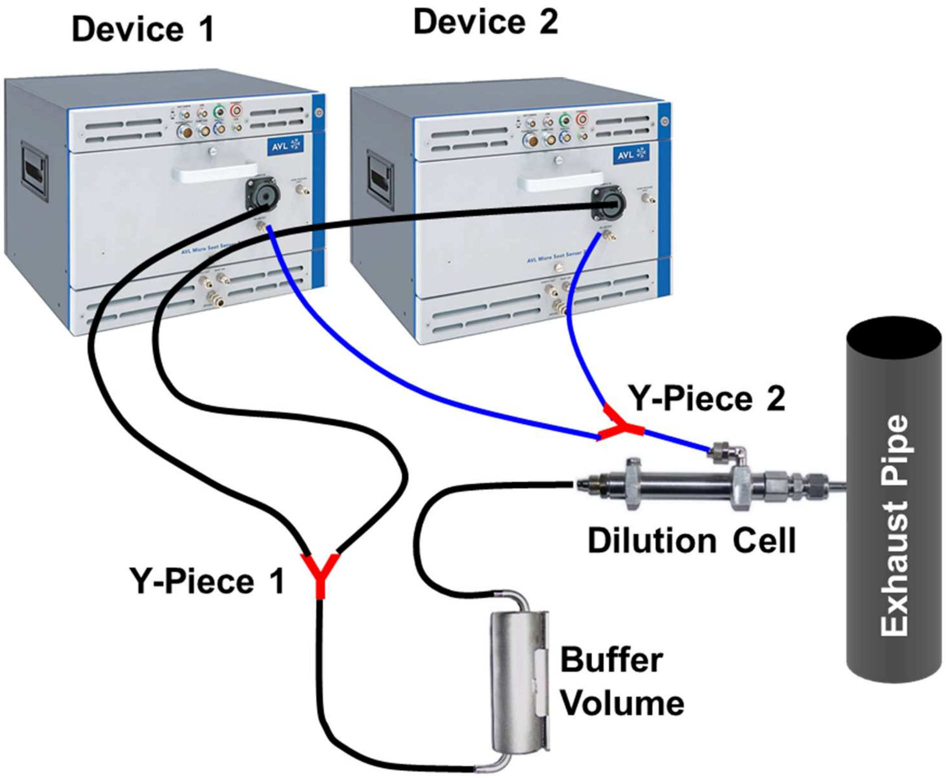


Figure 1: Setup for the alignment of two MSS on raw exhaust

If this procedure is carried out with care, the sensor units can be aligned within a window of 3%.

Case 2: Comparing the complete device setup (with or without dilution enabled)

This approach can be used to determine the deviation between devices on raw exhaust including the conditioning unit. This is helpful for determining the total uncertainty of the soot measurement with MSS devices. The comparison can be conducted for different dilution ratios. The results include the deviations caused by the dilution for the individual devices.

A schematic drawing of the setup can be found in figure 2. Use the standard sample lines and dilution cells attached to the device.

Step by step procedure:

1) Connect the probes of the candidate devices in a piece of straight pipe in the exhaust stack of a diesel engine (No DPF) in a backpressure-free area, as shown in figure 2. Make sure the exhaust is well mixed in the sampling area. **Do not use any flow splitter upstream the dilution cell!**
2) Now warm up the engine and select a steady state point with stable soot emissions. Avoid high load points. **No transient operation!**
3) The exhaust temperature at both sampling points should match as closely as possible (deviation < 30°C recommended). Colder exhaust is better than hot exhaust, the engine operation point should be selected accordingly.
4) Select the desired dilution ration on both devices and start a measurement. Record values for at least one minute and calculate the average to compare.
5) Swap out the sample positions to exclude sampling artifacts originating from the setup. The deviation should stay the same for each device, no matter which position the devices are sampling from. In case there is a deviation there might be insufficient mixing of the aerosol at the sample location. Make sure there is enough distance for homogenous mixing upstream the first sample point. 5 to 6 pipe diameters are usually enough.
6) More than 2 devices can be compared by using this method, if the exhaust pipe is long enough.

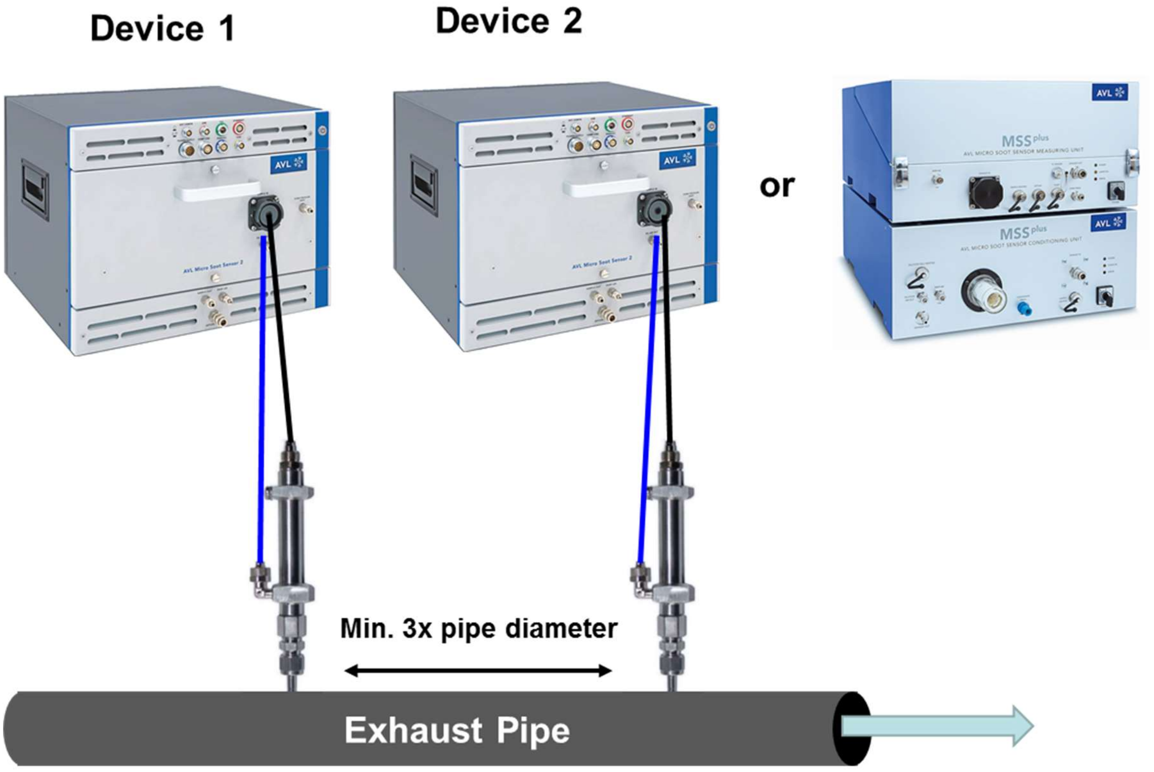


Figure 2: Setup for comparing two MSS devices and conditioning units on raw exhaust

Note for using an AVL APG for comparing instruments:

The above checks can also be carried out by using an AVL APG, in case one is available. Details about this use case can be found in the AVL APG Application Guide.

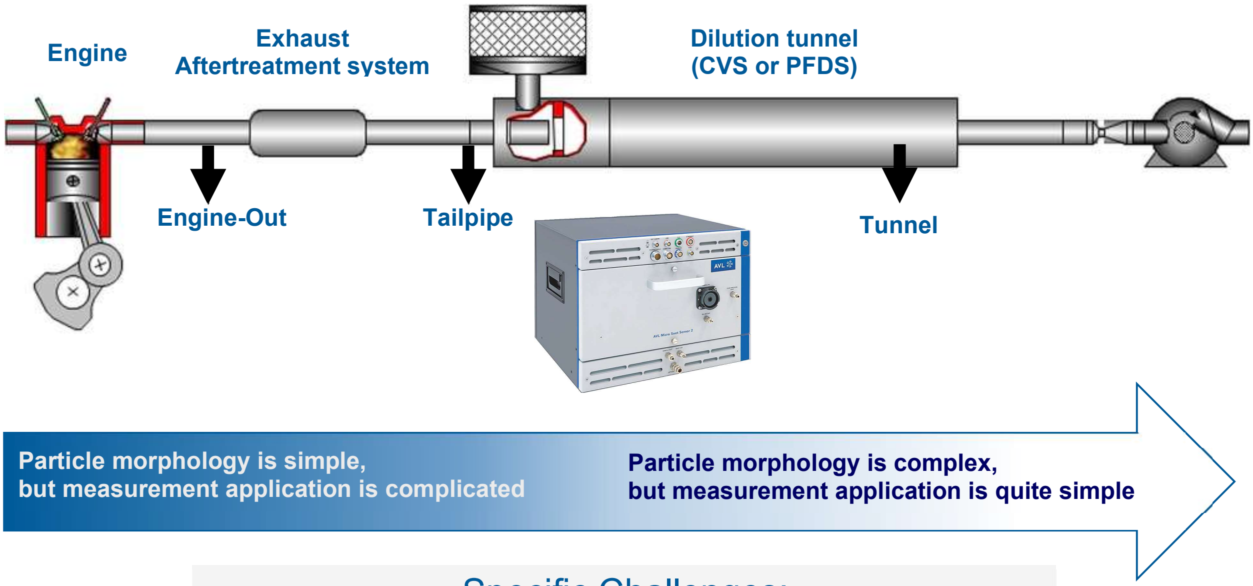
General notes for comparing instruments:

- Try to avoid T-pieces upstream of the devices. This may cause artifacts, especially when the exhaust is not well mixed. Y-splitters are preferred.
- Never use asymmetrical flow splitter setups, i.e. 3 instruments sampling out of one splitter.
- Do not use any flow splitter in the raw exhaust part prior to the dilution cell of the MSS.
- In any setup using flow splitters (like first example) make sure the sample flow on both branches of the splitter is identical.
- Instrument comparisons should always be conducted during stable engine operation. Transient operation may introduce artifacts and uncertainties due to time delay effects, turbulences, inhomogeneous mixing, etc.
- All hoses and the Y-splitter must be completely clean. Deposited soot particles can influence the result.

Even though the guidelines provided in this chapter mainly refer to the Micro Soot Sensor, they are applicable to any kind of aerosol instrument. Other instruments may react differently to artifacts compared to the MSS. The APC for example works with a higher sample flow and measures particle number. Mass separating effects, which have a big impact on the MSS, might show a much lower impact on the APC. Large particles (= high mass) are more sensitive to artifacts caused by turbulences, incomplete mixing, etc.

3. Sampling Locations

Figure 3 shows a schematic overview over the most common sampling locations and the related issues and requirements. The morphology of the particles is changing significantly while the exhaust is passing through the stack / tunnel, but the soot mass remains constant. On all sampling locations the total soot mass measured by the MSS should be the same (no particle filter in exhaust stack), if the application is set up thoroughly and losses are compensated (chapter 4).



Specific Challenges:

High pressure (≤ 2bar) High soot concentration High temperature (≤ 800°C) High HC concentration Inhomogeneous particle distribution	Temperature ≤300(600)°C or lower (from tunnel) Low soot concentration (or very low post-DPF) Possible Influence from exhaust composition High humidity (gasoline)

Figure 3: Different sampling locations and related challenges

3.1. Sampling from diluted Exhaust

This is the least challenging application for the MSS2. The preferred method for the measurement of soot is to sample from a dilution tunnel (CVS), because these systems minimize all sampling problems.

If the soot concentration of such a diluted exhaust is measured with the Micro Soot Sensor, no further dilution by the internal dilution system required. The dilution should be turned off (Option “No Dilution” in the DUI). See also chapter 3.5.1.3 in the MSS2 product guide.

3.2. Sampling from raw Exhaust

Sampling from raw exhaust is more difficult to handle than sampling from pre-diluted exhaust. In this application the internal diluter of the device must be used.

The Micro Soot Sensor requires dilution of the exhaust for the following reasons:

- The temperature of the hot exhaust must be reduced. The temperature of the measuring cell should not exceed 56°C for longer time periods, otherwise the microphone will degrade quickly. The temperature in the measuring cell is controlled to 52°C, but without active cooling.
- Water condensation inside the sample lines or in the measuring unit must be suppressed.

- Even though the MSS has originally been designed for high sensitivity (<1µg/m³), it can measure quite high soot levels. The measurement range of the MSS2 measurement cell has been increased compared to the previous MSS. On the upper end of the range it can handle a sensor concentration as high as 150mg/m³. If concentrations above 150mg/m³ should be measured, additional dilution is required to decrease the concentration to the operating range. It is also advisable not to expose the measurement cell to a sensor soot concentration >50mg/m³ for longer periods of time, since this will dramatically increase the pollution. In high flow mode (default setting) the bypass filter of the MSS2 will contaminate 2-3 times faster compared to the old MSS. See also chapter 3.2.5.

3.2.1. Tailpipe Sampling

From all possible sampling positions within an exhaust stack, the sampling from tailpipe is the most uncritical. It is advisable not to use the pressure reducing unit in this application. The MSS2 is designed to work at relative pressures between +60mbar and -500mbar (at sea level). At the outlet of an exhaust stack the pressure should be close to ambient level. Sometimes slightly negative pressures are observed, due to the suction of a connected venting system. In rare cases this may lead to a slight shift in the baseline of the measurement signal or other distortions. The signal of the detector microphone inside the measurement cell is compensated for pressure changes. Due to tolerances in the production of the microphones, the effectiveness of the compensation may vary slightly between instrument. The observed shift usually does not exceed +/-2 µg/m³ at relative pressures of +/-60mbar.

The standard sample probe (45° cut) is the first choice for tailpipe sampling. It should face upstream the exhaust flow. The particle distribution usually is quite homogenous at this location. Nevertheless, there should be certain part of straight pipe in front of the sample point (ideally 3-5 times the diameter). Behind the sample point there should be an additional 15-25cm of exhaust pipe to minimize the backflow of ambient air. For further information on probes and sample points see chapter 5.

Soot emissions downstream a particulate filter (DPF or GPF), are extremely low. A reliable measurement by gravimetric methods is quite difficult or even impossible. The Micro Soot Sensor, however, can still detect the low emissions from DPF-equipped vehicles. It is especially useful for detecting minor failures of the filter.

A special Issue may occur when the engine speed is generating exhaust pulsations in the frequency of the photoacoustic sensor system of the device (~4100Hz). In such case (very rare) a resonance can build up inside the exhaust duct, which will introduce a high amount of noise into the sensor signal. Sample points in closed pipe systems (e.g. to ventilation or CVS) or in long exhaust pipes are more prone to this issue. Figure 4 shows a worst-case example for this kind effect on the MSSplus. The only way to counteract this kind of problem was to use the PRU, even though the exhaust pressure at the sample position is close to ambient level. The PRU acts as a muffler but will introduce additional uncertainties (chapter 5).

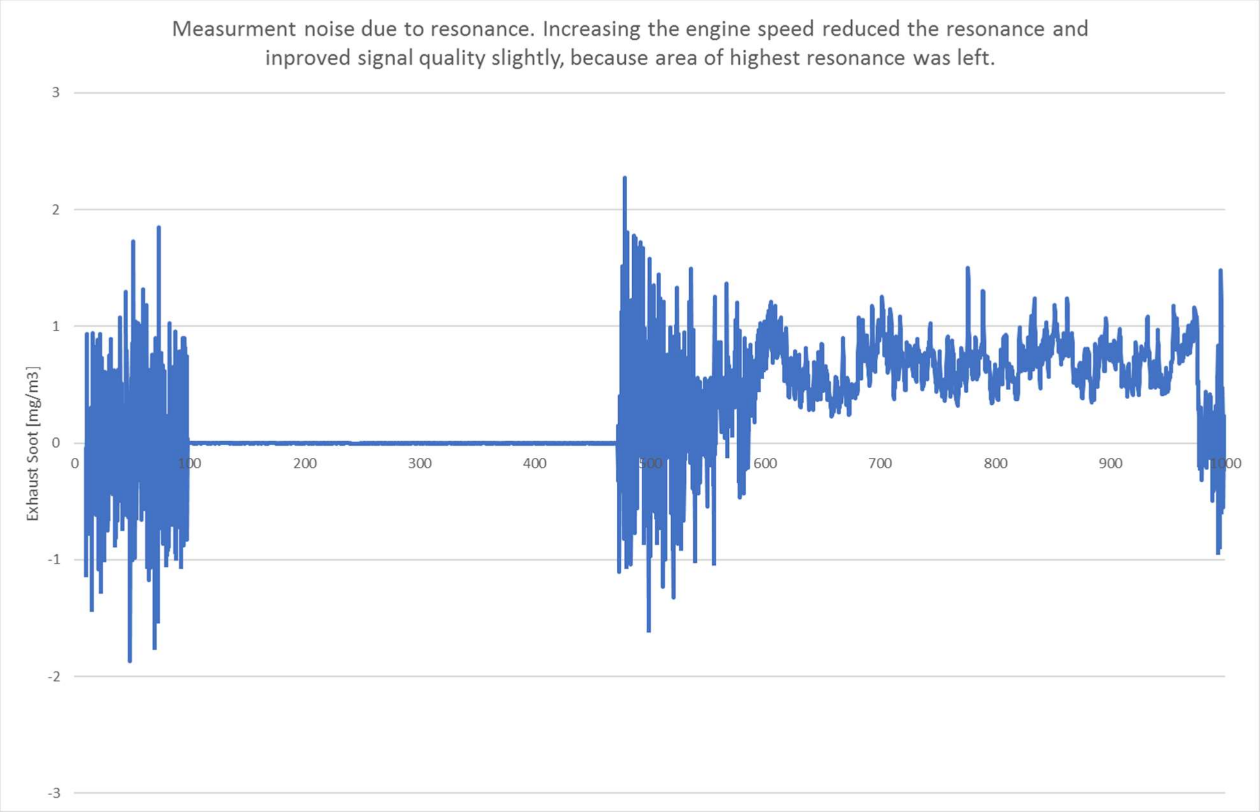


Figure 4: Distortion of the MSS sensor signal by resonance inside a closed exhaust duct, which was connected to a closed ventilation system

The MSS2 does show less issues in such a case. It features an improved acoustic filter, which helps to suppress external influences. Even if the PRU needs to be used, because the noise is too high for the filter, there are less issues than with the previous setup. The new PRU combined with the MSS2 performs much better in tailpipe applications (chapter 5). Figure 5 shows another example, where such distortions occur in the MSS signal. At the same time the MSS2 sampling in parallel was not affected.

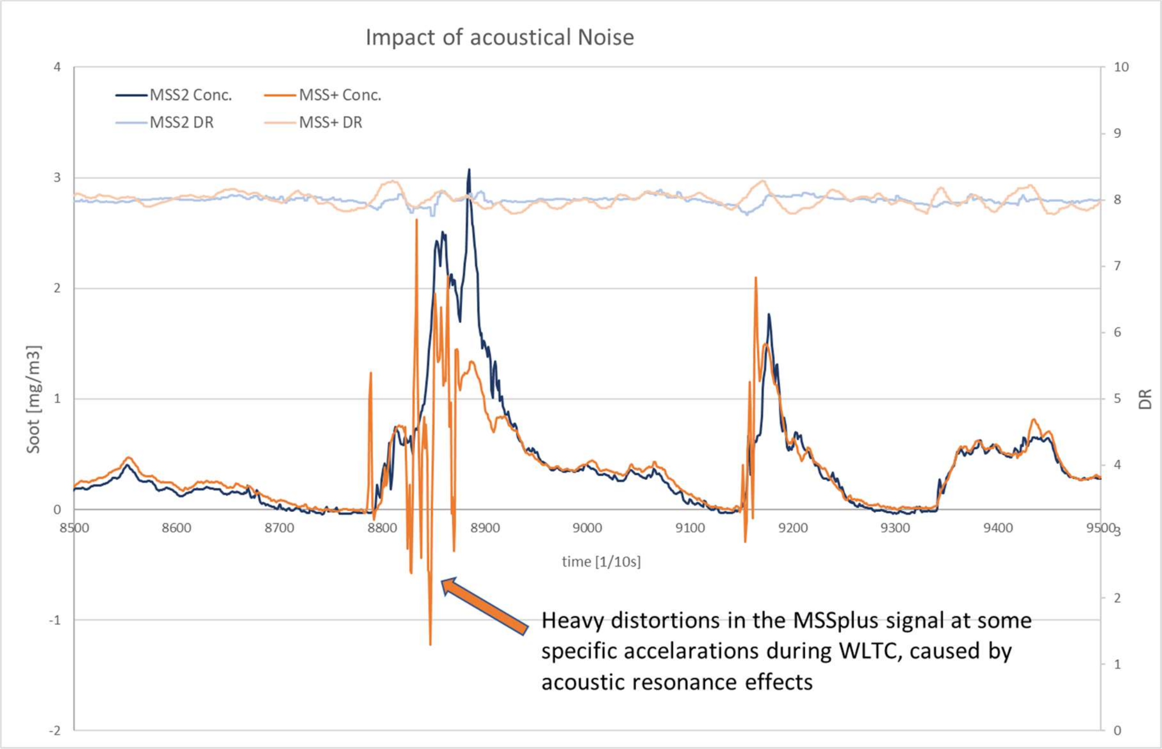


Figure 5: Acoustical distortion in MSSplus signal, MSS2 is not affected

Typical tailpipe applications are:

- Stationary and transient optimization if no filter is present (DOE)
- OBD soot sensor calibration
- Failure detection of DPF systems

3.2.2. Choosing the right Dilution Setting

As mentioned earlier in this chapter, sampling from raw exhaust requires dilution. The MSS2 offers dilution ratios from 2 to 20, which can be pre-selected by the user. For further information about setting the dilution ratio please check the MSS2 product guide (chapter 5.3.2). The following recommendations help to select the right dilution ratio:

1) A dilution ratio of DR=6 is a very good starting point for most applications.
2) The dilution ratio should be as low as possible (DR=3-6). But when using low dilution ratios on “dirty” exhaust, the measurement cell may get dirty very quickly. Ideally the sensor concentration should be <10mg/m3 most of the time. This combines good accuracy with acceptable pollution levels and allows for long measurement periods without clogging the bypass filter. Short peaks of high soot levels are no issue (example: cold start), since the MSS2 allows for sensor soot concentrations as high as 150mg/m3 (see introduction to chapter 3.2).
3) On diesel exhaust (lean combustion, carbon-rich fuel), humidity is no big issue. A dilution ratio of DR=2 is possible when using the heated sample line. This can be useful on very low soot concentrations (DPF).

4) Unfiltered diesel exhaust (engine-out) contains quite high amounts of soot. Here a higher dilution ratio is needed. A dilution ratio in the range of DR=6 to DR=10 will work just fine in most cases.
5) On gasoline exhaust a minimum dilution of DR=5 is highly recommended to suppress the condensation of water and to minimize other influences of the exhaust gas composition. The heated sample line should be used in any case.
6) The dilution should be high enough to cool down the sample gas to <60°C. Assuming the dilution air temperature is close to ambient level a dilution ratio of DR=3 would cool down the gas by a factor slightly below 3. Since a significant cooling of the gas already takes place in the probe and/or PRU, a dilution ratio of DR=3 should be good for exhaust temperatures up to ~450°C. At higher temperatures a minimum dilution ratio of DR=5 is recommended.
7) Dilution ratios ranging from DR=3 to DR=10 guarantee best performance in terms of accuracy and repeatability. Higher dilution ratios are less accurate (see equation 1) and more instable during pressure pulses (chapter 3.3.4 of this guide).

3.2.3. Engine-Out Sampling

Things become more difficult at engine-out sample points. In addition to everything mentioned earlier, much higher pressures and high temperatures make this application more challenging. Here in most cases the pressure reducing unit must be used. The PRU reduces the backpressure through an orifice. A certain amount of exhaust is blown out through the orifice, depending on the exhaust backpressure. Behind the orifice there is a homogenization chamber with a sample port, where the dilution cell of the MSS2 is connected. For more information about the PRU (working principle, application and maintenance) please see chapter 5.4 and the MSS2 product guide (chapter 3.2.2). The PRU reduces the backpressure close to the ambient pressure level. During highly transient engine operation the backpressure may change very quickly. In this case even behind the orifice of the PRU significant pressure variations can be observed (up to +/-30mbar). This range is the result of the instrument sampling out of the PRU at zero backpressure (pressure drop through orifice, negative pressure) and the check valve opening around 25-30mbar when the backpressure increases (see chapter 5.4 of this guide). Although this pressure level is still close to ambient and therefore no problem for the MSS2, it can have an impact on the dilution accuracy. The main cause for this effect is the pressure gradient, not the absolute pressure difference. The faster the pressure is changing, the more of a problem it is. Figure 6 shows an example on how pressure pulses can influence the dilution of the MSS2. The pressure pulses generate short fluctuations in the total system flow. The mass flow controller which controls the flow of dilution air must counteract quickly in order to keep the dilution ratio stable. Due to the pneumatic layout of the device, this takes a certain amount of time and thereby creates instabilities in the dilution ratio. The dilution accuracy gets compromised during such an event. However, even with the dilution ratio appearing unstable, the actual increase in dilution error is minor. Note that the error will increase with longer sample lines due to the additional time delay. Especially high dilution ratios are affected by this behavior. Therefore, a low dilution ratio should be selected (DR<10). Figure 6 shows the difference in dilution stability for DR=6 and DR=10 during a highly transient on-board measurement. The effect on DR=6 is very low, whereas at DR=10 it starts getting more significant.

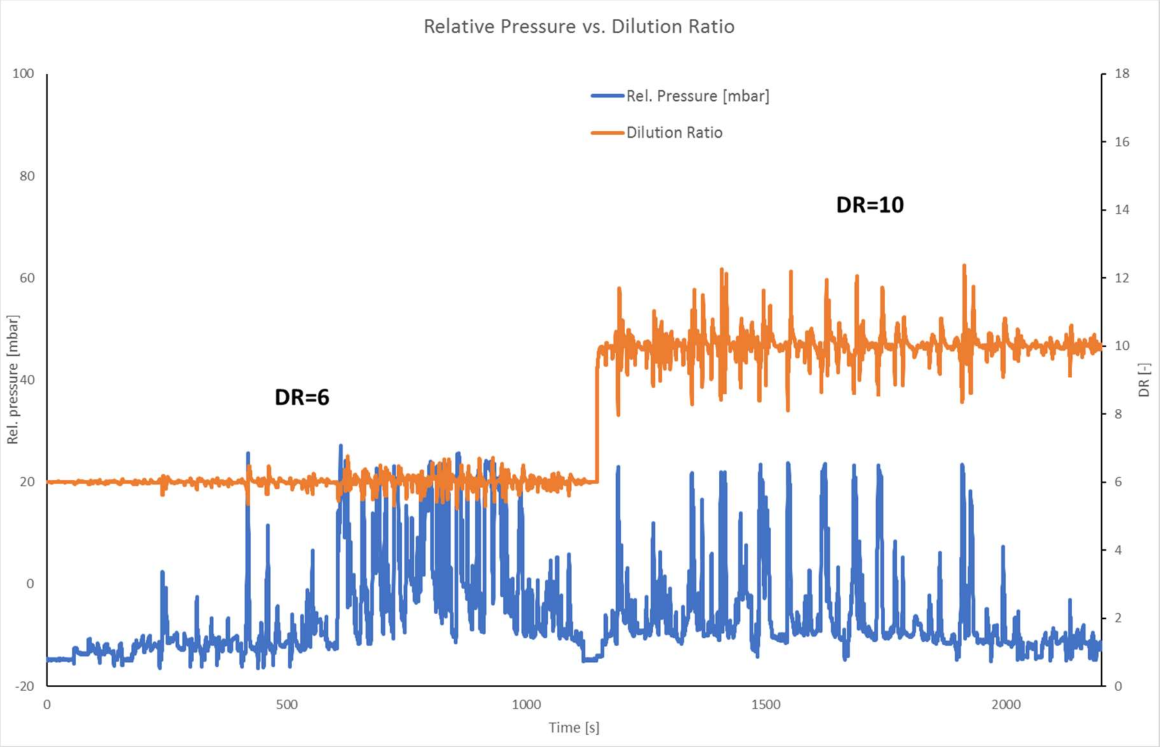


Figure 6: Pressure pulses can cause instable dilution

A thorough installation of the PRU can also help to minimize this effect (chapter 5.3)

A general issue for engine-out sampling is the particle distribution in the exhaust, which can be extremely inhomogeneous. Close to the engine it is even more important to have a piece of straight line in front of the sample probe. Unfortunately, this is impossible in many cases, because modern engines and aftertreatment systems have a very compact layout. This is necessary to keep the temperature at the exhaust aftertreatment system high to get good conversion ratios. In most cases there is just a short piece of bended pipe available to place a sample probe. Modern Diesel engines are usually equipped with turbo chargers and EGR systems, which complicate this application even further. In a bend right behind a turbo charger, strong turbulences occur inside the exhaust pipe. Higher EGR rates could distort the particle distribution even further. Very often multiple aftertreatment stages (DOC, DPF, etc.) are "canned" into one single cabinet. Sometimes there is some free space between the components. In this case the catalyst acts as a kind of homogenizer. If an LNT system is mounted in front of the DPF, a substantial amount of NH_3 and NO_2 could be present at the same time. Upon cooling ammonium nitrate (NH_4NO_3) may crystalize inside the colder areas of the sampling system. In a few cases this problem has been observed with emission measurement equipment. It has not shown up with the MSS/MSS2 so far, but it is advisable to check the sample inlet and the hoses in front of the measurement cell for deposition of white particles.

According to the experience, the results are still trustworthy in most cases, even at difficult sampling locations. The uncertainties are usually greater during highly transient operation. During less dynamic cycles the results will be more representative.

For further information on the appropriate sampling setup see chapter 5.

Typical engine out applications are:

- Engine-out soot map (diesel)
- Stationary and transient optimization (DOE)
- Determination of soot loading on DPF or GPF
- Validation of filter soot loading model
- General engine calibration work and combustion development

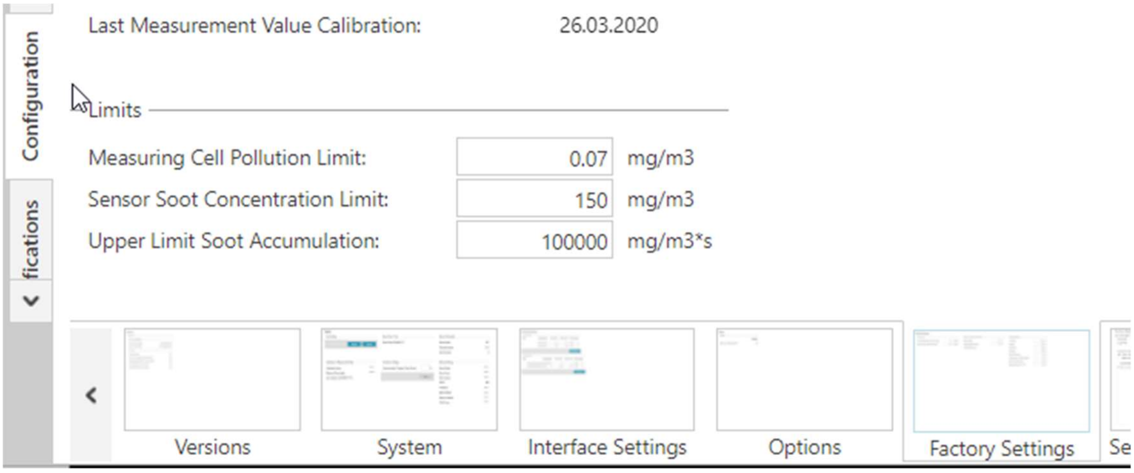
3.2.4. Handling high Soot Concentrations

When measuring high soot concentrations (especially at engine-out locations) the user is facing a kind of dilemma: The exhaust must be diluted, but the dilution should be kept as low as possible. In many applications it will be impossible to keep the sensor concentration below the recommended level of 10mg/m3 (or 50mg/m3 for short time, chapter 3.2.2 of this guide).

The MSS2 allows for a higher sensor concentration than the previous generations of the MSS. It is possible to process a sensor concentration as high as 150mg/m3 without compromising the linearity of the signal. This provides a lot more flexibility for cold-start measurements. It is possible to operate on an overall higher soot level than with the MSS, but pollution will increase rapidly.

Concentrations >150mg/m3 will trigger an error message (product guide chapter 10.2.47). the device will switch from MEASUREMENT to ZERO CHECK for self-protection. After 10 seconds it will switch back to MEASUREMENT. No measurement values are transmitted during this period. This should be kept in mind when setting up automatic test runs. In case of a continuous measurement, AVL Puma 2 will store overflow values in the result dataset while the instrument is in self-protection mode.

The upper limit for the sensor concentration can be adjusted by using the DUI or the AK command ESCL in user level ENGINEER (MSS2 product guide 7.2.2.11). As with the MSSplus the levels for the pollution warning can be adjusted as well in user level ENGINEER. This can be done by using the DUI (Figure 7) or with the AK command EWPL (MSS2 product guide chapter 7.2.2.14). The pollution warning will not stop or compromise the measurement.



Last Measurement Value Calibration: 26.03.2020

Limits

Measuring Cell Pollution Limit: 0.07 mg/m3
Sensor Soot Concentration Limit: 150 mg/m3
Upper Limit Soot Accumulation: 100000 mg/m3*s

Figure 7: Setting limits for pollution warning and measurement range in the DUI

An additional problem related to running on high soot levels with longer cleaning intervals is the increasing pollution of the exhaust inlet valve in front of the measurement chamber. Often an increase in signal rise time and resolution is caused by contamination of this valve. Whenever the measurement cell or the windows get cleaned, the inlet valve should be cleaned as well. Simply blow some compressed air through the open valve from the inside to the outside. The valve can be opened by using the switch on top of it. A description of the whole cleaning process can be found in the MSS2 product guide (chapter 8.1).

3.2.5. When to use full Flow and reduced Flow on the MSS2

As has been mentioned in the previous chapters of this guide, the MSS2 can be operated on a high and a low flow setting. Both settings are linked to several advantages and disadvantages. The most obvious advantage of a high flow is the improvement in signal rise time and response time. The higher probe flow for any give dilution setting will help to improve dilution stability. At the same time the higher flow through the bypass will lead to higher pollution of the bypass filter and the inlet valve, as described in the previous chapter. As a general recommendation, the high flow should only be used if high signal speed is required (e.g. monitoring tip-in events) or when high dilution rates are needed (e.g. DR>10). In some applications a long sample probe (>25cm) in front of the PRU is required due to room restrictions. Whenever this is the case, the high flow setting helps to reduce time delay during low pressure phases. However, a setup with very long probes should be avoided (see chapter 5 for details) In all other applications, the lower sample flow is preferred. Note that due to the lower dead volumes in the sample path (compared to MSSplus) the signal speed is slightly improved anyway.

3.2.6. Frequency Tracking and Humidity Compensation

The function “Zeroing with exhaust” was used to eliminate effects deriving from the exhaust composition (pressure effects as well as changes in the sonic speed due to the exhaust composition). There are only very few applications where such effects may occur like measuring low soot in a nitrogen-rich exhaust. Nitrogen has a significantly different sonic speed than air.
The function “Zeroing with exhaust” is not available on the MSS2 due to the pneumatic design of the device. In order to compensate the effects described earlier, real-time frequency tracking has been implemented. The function can be enabled/disabled in the DUI (MSS2 product guide, chapter 5.3.1.3).

4. Sampling Losses and Deposition Mechanisms

When sampling from raw exhaust sampling losses are nearly unavoidable. This chapter briefly explains the nature of the different deposition mechanisms and possible countermeasures.

4.1. Turbulent Deposition

Turbulent losses occur whenever the aerosol passes bends or edges. This causes turbulences in the sample stream which lead to deposition effects, as shown in figure 8. The particles build up “dunes” behind physical barriers in the sample stream. In case of the MSS, the pressure reduction unit is the major source for turbulent losses. This device will add 5-7% of additional particle losses (see chapter 5).

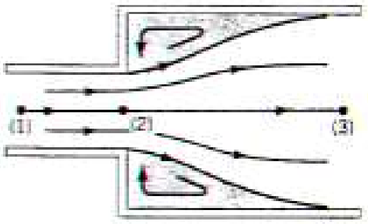


Figure 8: Schematic drawing of the turbulent deposition mechanism

4.2. Diffusional Losses

Small particles in an aerosol are influenced by the Brownian motion. They move along with molecules of the carrier gas. This is called diffusion. When the particles hit the wall of the sample line, they normally stick on the surface. In “wet” exhaust (high HC and/or water content) the probability that a particle sticks on the wall is higher than in “dry” exhaust. This effect can be reduced by proper dilution (conditioning) of the exhaust. The amount of diffusional loss increases linearly with the sample line length. Therefore, sample lines should be kept as short as possible (chapter 5). For instruments measuring particle mass, like the MSS, diffusional losses are not as significant as for number counting instruments (i.e. AVL APC), as they affect smaller particles with lower mass more than larger ones.

4.3. Losses due to Thermophoresis

When sampling from raw exhaust sampling losses are nearly unavoidable. Thermophoretic losses always occur when an aerosol cools down along a temperature gradient. Like diffusion, thermophoresis is related to the Brownian motion. In contrast to the statistical diffusional movement, the thermophoretic movement is directed along a temperature gradient (thermo-diffusion). The Brownian motion of the surrounding molecules in the warmer areas is faster than in the colder areas, hence the gas molecules hit the particles more often and with more momentum on the “warmer” side. The aerosol particles get pushed to the cold walls, as shown in figure 9. This effect leads to major deposition of particles. Thermophoresis can only be eliminated by sudden cooling of the hot exhaust via dilution. All other sampling and dilution methods suffer from thermophoretic losses. Unheated pipes of stainless steel cool down quickly at low gas flow. This can be as much as a few hundred °C within 10cm of sample line. Heating the sample to exhaust temperature until the point of dilution would reduce the losses, but this is technically hard to implement. It is much easier to compensate the losses by a calculation as described below.

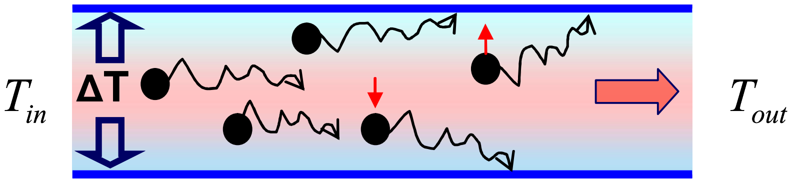


Figure 9: Principle of the thermophoretic deposition mechanism

Thermophoretic losses can be calculated by an empirical equation according to ISO 8178-1 Annex C.1:

$$\frac{c_{out}}{c_{in}} = \left(\frac{T_{out}}{T_{in}}\right)^{0,38} \qquad \text{(Temperatures in Kelvin)} \qquad [2]$$

The loss factor for the sampling probe can be calculated when the exhaust temperature (T_{in}) is measured closely to the sample point. T_{out} can be assumed to be the temperature of the heated dilution cell (120°C), when used. With an unheated sample line, one could use a value close to ambient temperature, but experience shows a tendency to overestimate the losses in this case. It is advisable to set T_{out} to 120°C (393K), even if no heated dilution cell is used. This may cause a slight underestimation of losses at low ambient temperatures in some cases, but for low exhaust temperatures the uncertainty of the loss compensation gets quite high anyway. At lower temperatures the amount of thermophoretic losses gets low compared to other loss mechanisms, which do not show such a good reproducibility and vary much more between different applications (turbulences, diffusion and sampling artefacts). It is preferable to use 120°C in any case and not to apply a correction at lower temperatures. Since most of the cooling occurs in front of the dilution cell, there should be a dependence of the losses in the dilution ratio. Higher dilution means lower probe flow, and thereby more heat exchange through the probe walls. Practical observations have shown that there may be slight differences when using very low or the very high end of the dilution range, but for the dilution ratios where the instrument shows best performance (3-10), the effect is negligible. When a pressure reducing unit (PRU) is used, the cooling prior to the dilution cell also depends on the residence time in the PRU, which is directly linked to backpressure and sample flow. Since the new PRU for the MSS2 has been optimized for flow, the impact is lower compared to the MSS and the previous PRU (see also chapter 5.4).
Taking these considerations into account, equation 3 can be used to convert the measured soot concentration into the loss-corrected exhaust soot concentration.

$$c_{exhaust} = \frac{c_{measured}}{\left(\frac{393K}{T_{exh}}\right)^{0,38}} \qquad \text{(Temperatures in Kelvin, no compensation for T<393K)} \qquad [3]$$

Figure 10 shows the compensating effect of equation 3 when applied to the uncorrected exhaust soot concentration.

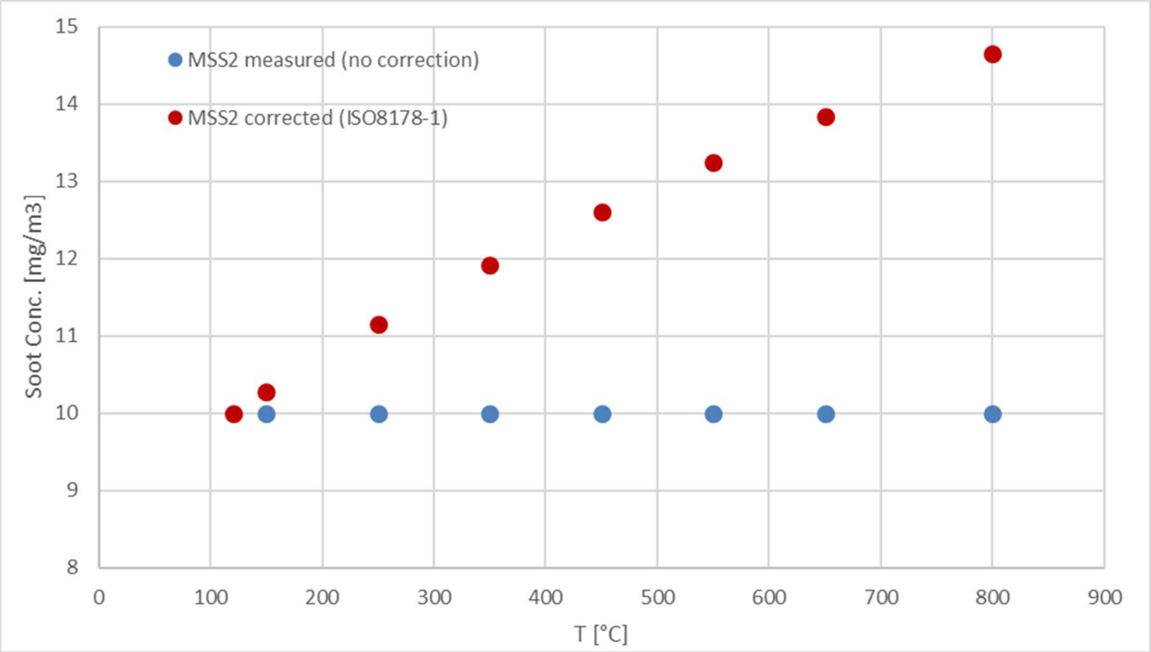


Figure 10: Effect of thermophoretic loss correction using equations 3 on a measured soot concentration of 10mg/m3

The MSS2 offers the exact same built-in compensation for thermophoretic losses as the MSSplus. The exhaust temperature is measured inside the sample probe by an integrated thermocouple. In addition to the dilution corrected concentration (exhaust soot concentration) a channel with the applied loss correction is offered. For more details about the setup please check the MSS2 product guide (chapters 3.3.3 and 3.5.1.3). The device uses equation 3 to calculate the thermophoretic losses based on the temperature values read by the thermocouple. Figure 11 shows a measurement during an NEDC. Note that this measurement was taken by an MSSplus. The MSS2 results would look the same. Over the whole cycle the loss compensation increases the measured soot mass by approximately 10%. In this example the exhaust temperature remains comparably low, because it was a diesel engine running a moderate cycle.

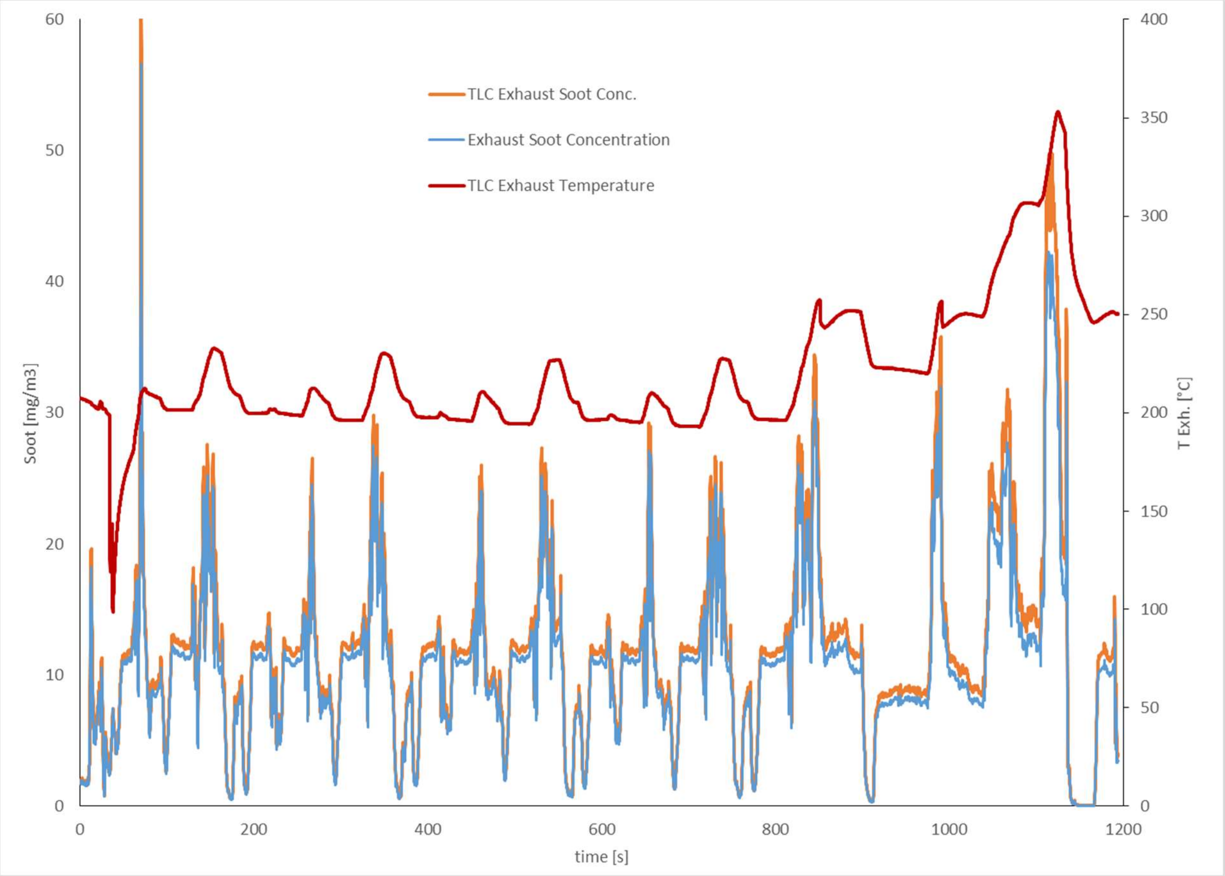


Figure 11: Corrected soot concentration obtained by the MSS plus during an NEDC (hot). The MSS2 uses the exact same compensation.

The effect can be expected to be higher on more dynamic cycles (WLTC, FTP, etc.), especially when a gasoline engine is used. Figure 12 shows an example for the last phase of the WLTC on gasoline exhaust. Here an exhaust temperature of 450°C is reached, which correspond to a loss correction of 25%.

The corrected soot value is displayed as “TLC Sample Soot Concentration” in the DUI (MSS2 user guide chapter 5).

If data originating from measurements with the old MSS shall be compared to MSS2 data, it is advisable to use equation 3 for post-processing the MSS data in order to get the best comparability.

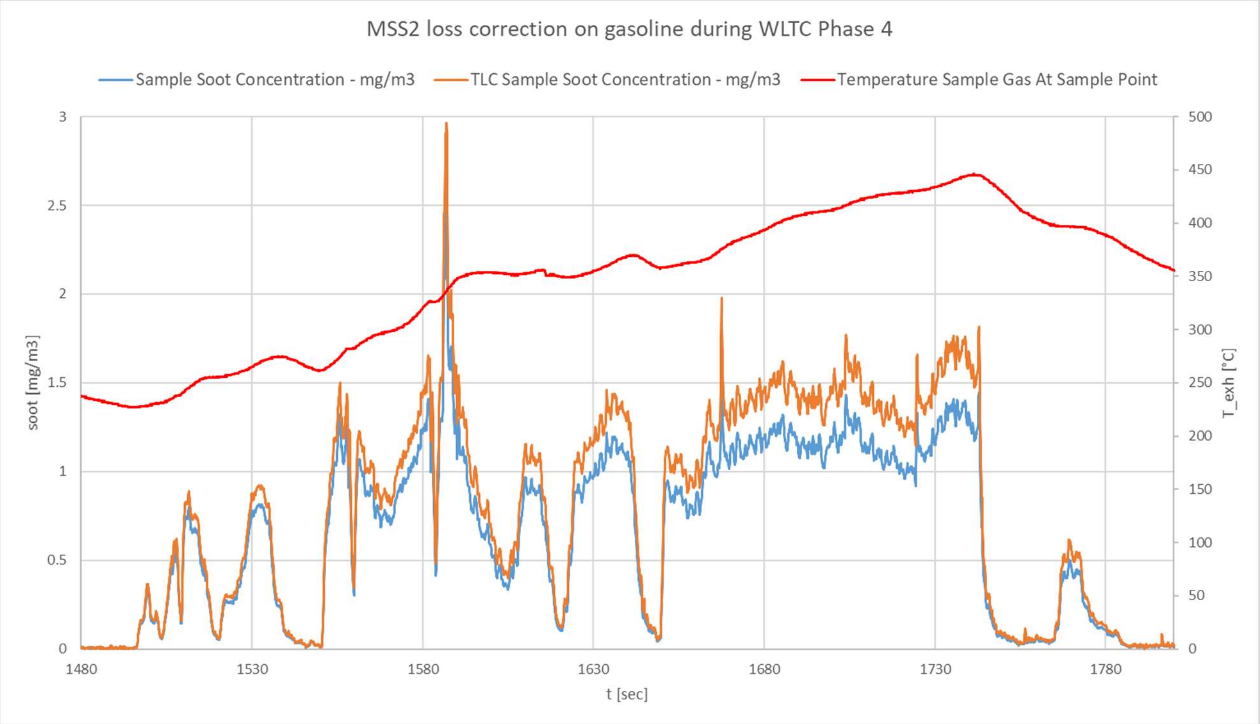


Figure 12: Corrected soot concentration obtained by the MSS2 during WLTC phase 4 on gasoline (GDI) exhaust.

4.5. Further Causes of Particle Losses

One of the most crucial problems when sampling from raw exhaust is the formation of condensed water upon cooling. If water droplets deposit on the inner surface of sampling or transfer tubes, irregular deposition of particulates may occur. The biggest problem here is that wet surfaces do not always induce significant losses. Particle deposition occurs sporadically and cannot be predicted. Condensed water in the sample lines and probes can be avoided by proper conditioning, short probes and the use of a heated sample line (see chapter 5).

Another loss mechanism is the electrostatic attraction caused by charged tube walls. Electrostatic effects can appear when the wrong material for the sample line is used. We strongly recommend the use of hoses provided by AVL for particle sampling. These materials have been tested to match the requirements (see chapter 5).

Losses produced by water and electrostatic effects are irreproducible and cannot be compensated by data postprocessing.

5. Sampling Setup

This chapter discusses the practical aspects of sampling particles from exhaust.

5.1. Sample Probe Position

In order to obtain representative measurement results, it is required to sample from a point where the particle distribution is homogeneous over the exhaust duct diameter.
In the pipe bends right downstream of a turbo charger, for example, a homogeneous particle distribution over the exhaust duct diameter is most likely not found. Sampling from such points should be avoided. Ideally there should be a piece of straight exhaust pipe with a length 6 times the pipe diameter in front of the sample point. In the case of multiple instruments sampling from the exhaust duct, they should be placed in a way they won't distort the MSS. Figure 13 shows a schematic overview of sampling locations for typical instruments with the recommended distances between the probes.

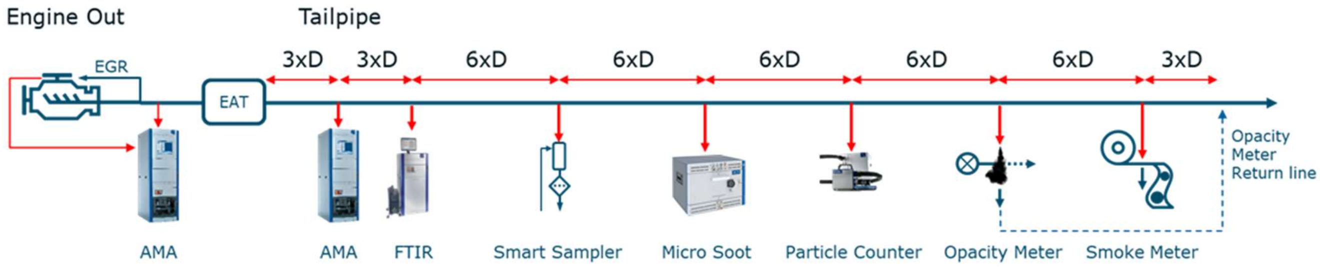


Figure 13: Recommended sample positions for multiple measurement devices in a straight exhaust duct

5.2. Sample Probes

The sample probe must be made of conductive, non-corrosive material. We recommend using stainless steel with a polished surface. As already mentioned even a relatively short probe upstream the dilution cell or PRU will decrease the measured particulate result due to thermophoresis. At medium dilution ratios (DR=6-10) the maximum amount of cooling along the probe is already reached after ~10cm outside the exhaust stack. Even much longer sample probes (up to 100cm), may not show any significant increase in thermophoretic particle deposition. Another problem related to the cooling is water condensation inside the probe. Even if the exhaust temperature is e.g. 450°C the temperature of the sample is ~50°C after 30cm of sample probe length and decreases even further for longer probes (~30°C after 50cm, etc.). At a temperature below 55°C the risk of water condensation increases drastically in diesel exhaust. For gasoline exhaust the temperature should be >65°C in order to avoid the condensation of water. Theoretically an additional heating of the probe could eliminate these problems, but in this case the temperature must be kept constantly high all the way from the exhaust pipe to the dilution cell. This is only achievable with a high technical effort.

If the testing time is extended, the measured concentration may decrease further. This decrease can be either permanent or temporary. The inner walls of the probe get coated with soot. The impact of this coating increases with the probe length.

Different types of probes are available, standard probes (open-faced, 45° cut probe) as well as multihole probes). The standard probes are most commonly used for MSS applications.

The inlet of the standard probe should be facing upstream in the center of the exhaust pipe, as shown in Figure 14. Additional information about installing the probe can be found in the MSS2 product guide (chapter 4.5.5). An exception from this rule are cold-start tests on gasoline vehicles with tailpipe sample position. Here the probe should be facing downstream. This will prevent water droplets from getting sucked into the sample line.

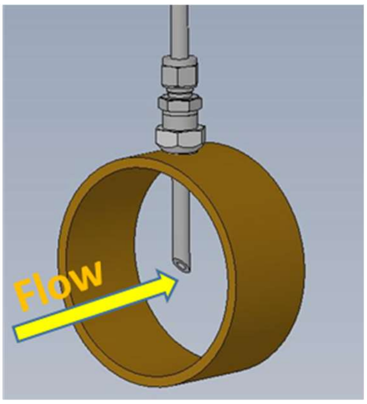


Figure 14: Mounting of the standard probe

The AVL standard probes for the MSS feature an outer diameter of 8mm and a wall strength of 2mm. Another probe type with only 1mm wall strength (6mm inner diameter) is available, too. The latter is designed for the use with the integrated thermocouple for the thermophoretic loss compensation feature of the MSS2. The inner diameter is increased to compensate for the room occupied by the thermocouple inside the probe. Figure 15 shows the components of the whole probe kit, containing the modified standard probe, a Y-piece with the thermocouple mount and the thermocouple itself. While the MSS2 requires a thermocouple with a special connector, the kit can also be used to mount standard type-K thermocouples. The reading of this sensor can be recorded by the test cell system for compensation of thermophoretic losses in the automation system or via post-processing. This can be useful when an older generation MSS without automatic loss correction is used. Make sure the tip of the thermocouple is well inside the exhaust pipe! The temperature reading must be taken in the hottest area to guarantee for a correct loss compensation.

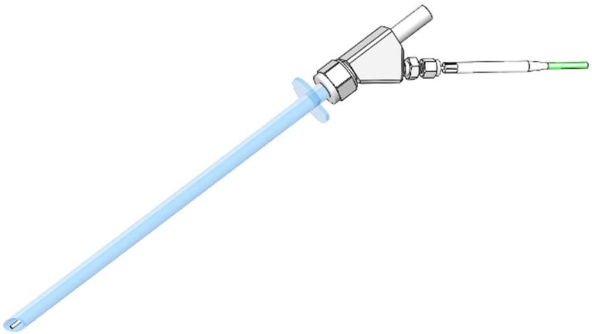


Figure 15: The MSS2 probe kit with an integrated thermocouple

If a multihole probe is used, it should cover the full diameter of the exhaust pipe and the holes must be evenly distributed over the surface of the probe. Surface-optimized multihole probes for different pipe diameters are available. An overview is shown in Figure 16. Multihole probes work best in application with high sample flow (high pressure with PRU, see chapter 5.4, or MSS2 in high flow mode with low dilution). A typical use case are engine-out locations with incomplete mixing and high backpressure. The tip of the thermocouple for loss compensation should be placed somewhere in the middle of the multihole probe.

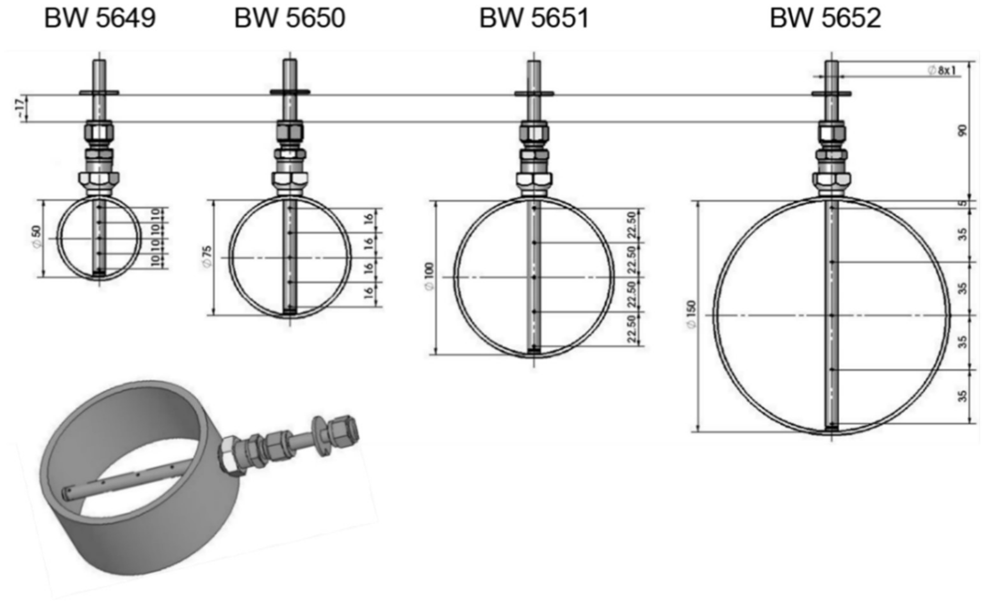


Figure 16: Available sizes and correct installation of AVL multihole probes

Probes should be as short as possible, but not shorter than 100mm (see next chapter). The dilution cell or pressure reduction unit should be as close to the exhaust as the temperature and/or pressure situation allows. Longer probes are especially critical at cold ambient temperatures. The risk of water condensation increases with the length of the probe. The probes are also suitable for the use with an internal thermocouple, because the inner diameter is 6mm.
For an overview of available probes see the MSS2 product guide (chapter 4.3).

5.3. The Problem of Backflow

Pressure pulsations and pressure changes cause a non-constant flow velocity. Besides the already mentioned negative effects on the dilution ratio, it could induce a backflow into the probe up to the dilution point. If the probe is too short, dilution air may escape into the exhaust pipe during the backflow periods. In this case the actual dilution ratio is smaller than the one measured by the device. It is obvious that such effects cannot be predicted. A minimal probe length of 100 mm is recommended, even if the exhaust gas pressure pulsations appear to be low.

5.4. The Pressure Reducing Unit(s)

At engine-out sample points we usually face high pressure and high temperature. Here the pressure reducing unit (PRU) must be used. The PRU reduces the backpressure through an orifice (1.75mm diameter). Behind the orifice there is a homogenization chamber with a sample port. The excess flow leaves the PRU through a check valve which is connected to the PRU body via a 40cm flexible steel hose. The check valve suppresses the backflow of ambient air into the sampling system, when the backpressure is low. Two types of pressure reducing units are available for use with the MSS2 (see also MSS2 product guide chapter 4.4):

1.) A 1-bar version (TM0497HPO1.01). This PRU is very compact and has been designed specifically for the use with the MSS2. The orifice is directly drilled into the metal body. Behind the inlet one sample port is located. This is where the dilution cell gets installed. It is easy to install in tight engine compartments and offers better signal dynamics due to the low dead volume. On the other side it provides low heat exchange with the environment, which makes it less useful in applications with very hot exhaust.
2.) A 2-bar version (TM0497HPO2.01). This PRU is significantly bigger than the 1-bar version. It was already available for the MSSplus and is also used for the AVL APC or the AVL Smokemeter. Behind the exhaust inlet an orifice plate is mounted on top of a spring. A certain amount of exhaust is blown out through the orifice, depending on the exhaust backpressure. This PRU is features two sample ports. The dilution cell of the MSS2 is connected to one of these ports. A typical engine-out application for gasoline development would use this PRU with an APC connected to the second port. At backpressure levels close to ambient, most of the exhaust gas flows around the orifice plate. The PRU can be operated permanently at temperatures up to 600°C and 2 bar backpressure. Higher temperatures (max. 1000°C) are possible for shorter time.

Figure 17 shows a drawing of the inlet area of both PRUs. Figure 18 highlights the differences in design and size.

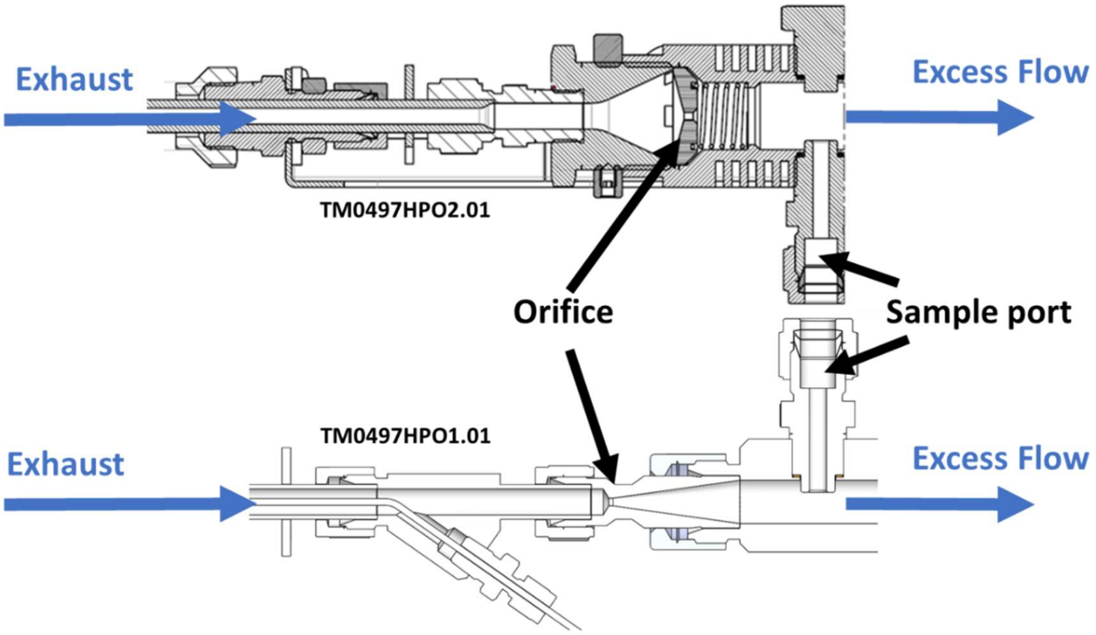


Figure 17: Comparing both PRU versions – inlet design

Figure 18: PRU 2-bar (top) vs. PRU 1-bar (bottom)

Both versions of the PRU share the same type of check valve, which contains Viton O-rings as sealing components. This limits the temperature range of the PRU. In practice the exact limit depends on the amount of flow through the PRU and the heat exchange with the environment. If hot exhaust at high backpressure shall be sampled, the 2-bar PRU should be used. It is also possible to extend the flexible steel hose in front of the check valve (extensions of different length are available, YMM4438 for 40cm, YM6126 for 100cm). This allows a better cooling of the exhaust. In any case the O-rings should be inspected frequently and need to be replaced when damaged. A leak check with mounted pressure reducing unit should be conducted in order to ensure that the check valve is closing correctly. A leak rate of <10mbar*l/min is acceptable. An exception are altitude simulations (ACS application, chapter 7.3). Here the PRU must be as leak tight as possible, ideally with a leak rate <6mbar*l/min.

Figure 19 shows a typical blow-off curve of the 1-bar pressure reducing unit. Tolerances can lead to a certain amount of variation between different units. The curve represents an average. It can be used to correct the exhaust flow measurement for other instruments mounted downstream, if necessary (like for small engines).

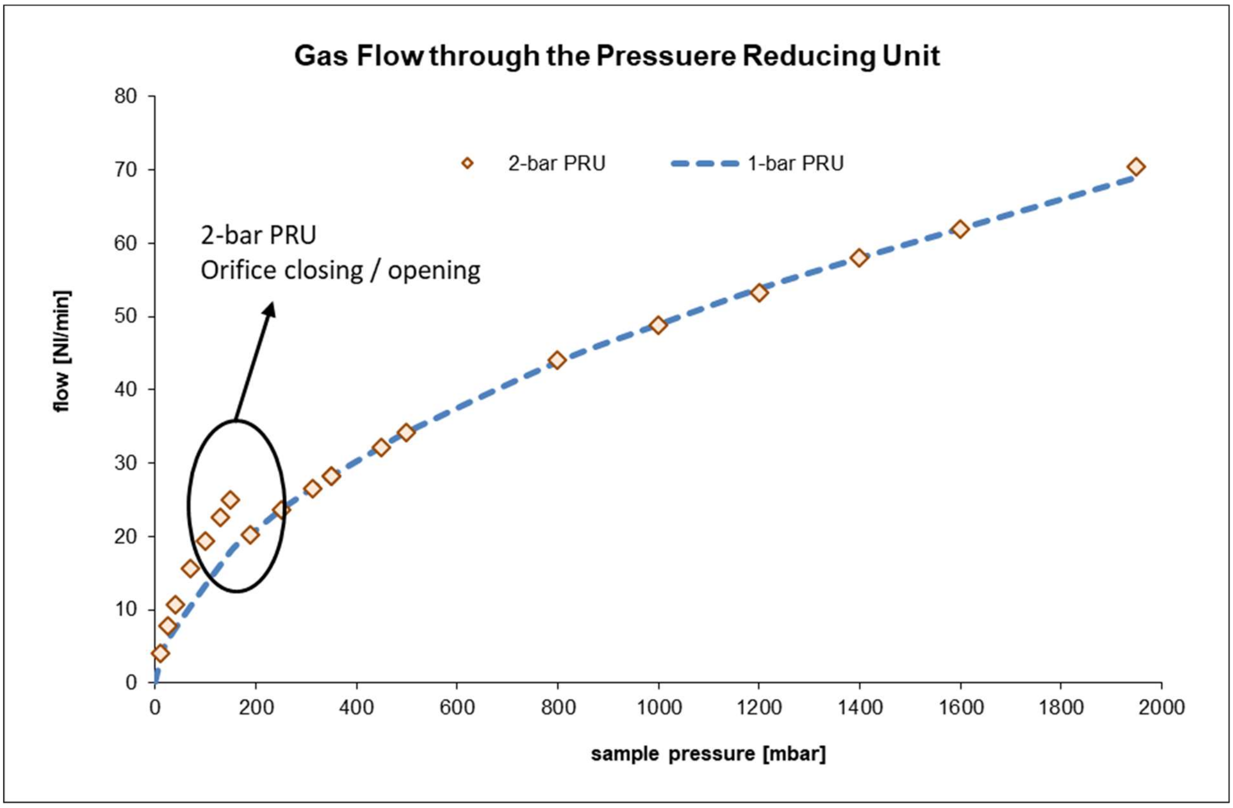


Figure 19: The averaged blow-off curves of both PRUs look the same, except a gap in the region of the orifice switch-point for the 2-bar PRU

Particle deposition – mainly due to the thermophoretic effects, but also to turbulent deposition – cannot be avoided. Whereas thermophoretic losses may increase marginally when using the PRU, additional losses due to turbulent deposition become more significant. Typically, a pressure reduction unit adds an additional 5-7% of particle losses.

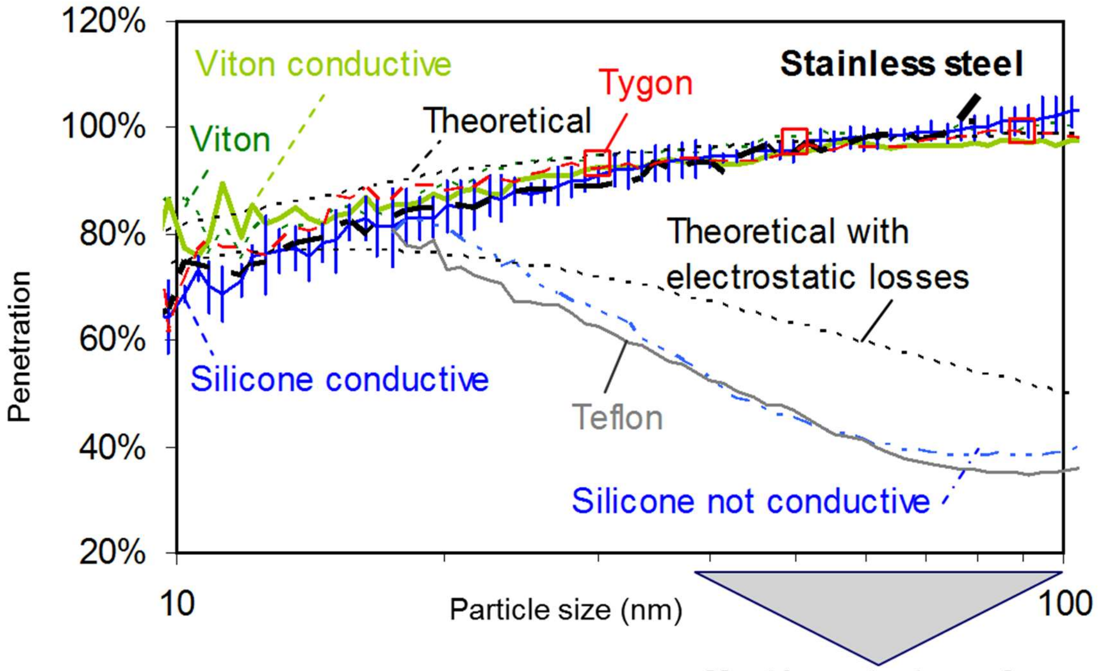
The 2-bar PRU should only be used where it is absolutely required. At sample points with low backpressure a decrease in time-resolution (less dynamic signal due to tailing) is unavoidable. This effect increases with the dilution ratio. With the high flow setting of the MSS2 or an APC sampling out of the same PRU this effect is less obvious, since in both cases the sample flow is increased.

The PRU should be installed in a way that the check valve at the end of the flexible hose points downwards. This allows water to run out of the unit. In addition, this kind of setup decreases the release pressure of the valve (~10mbar lower than with an outlet pointing upward), see also chapter 5.7. This also minimizes pressure pulses and leads to a more stable dilution (chapter 3.2.2). The probe should be mounted as usual, from the top half of the exhaust pipe. The dilution cell of the MSS should be mounted on the top side of the PRU, not at the bottom (chapter 5.7). This prevents condensed water from getting sucked into the sample line.

The pressure reducing units need some cleaning and maintenance. A simple cleaning method is to blow compressed air of 3-4bar into the side port, were usually the dilution cell is connected. This will purge the low-pressure part of the unit including the flexible steel hose and the check valve at its end. The same can be done for purging the high-pressure region by blowing the air into the sample probe port. For a more intense cleaning the unit should be disassembled. See the MSS2 product guide (chapter 8.9.2) for details on cleaning.

5.5. Transfer Line for diluted Exhaust

The sample transfer hose should be as clean as possible, because a dirty hose will increase the number of particles sticking to the wall. For a Tygon hose this means it should be transparent. This must be regularly checked for the sample line, as well as for the short piece of Tygon hose between the exhaust inlet to the instrument and the measuring chamber. If anti-static (black, non-transparent) Teflon (FEP or PTFE) or Viton hoses are used, they should be exchanged regularly. The heated sample lines contain anti-static Teflon hoses. These should be replaced approximately every 500 operating hours but latest during the 1000-hour services. Non-conductive Teflon hoses must never be used because significant electrostatic deposition effects can occur (see chapter 4.5). Figure 20 shows the particle penetration rates for sample lines of different materials. Losses of large particles (diameter >30nm) have a bigger impact on the mass based MSS signal. Especially the heavier particles (right half of the diagram) are affected by electrostatic effects, whereas the losses by diffusion are lower than for small particles.



Most important area for measurements with MSS

Figure 20: Particle penetration rates for different types of sample line materials

It was found that the length of the sample transfer hose downstream the diluter has only a minor effect on the measured particulate concentration (for stationary conditions). As a rule of thumb additional losses of 0.5-1% per meter of sample line can be assumed. Sample line lengths up to 6m are considered non-critical. However, an increased tailing of peaks during transient testing may occur when a long line (>4m) is used.

A heated sample line suppresses water condensation at chilly ambient conditions. Heating to 52°C (default) is enough for the diluted exhaust. A heated line should be used whenever possible but is strongly recommended at ambient temperatures below 20°C. When sampling humid (eg. gasoline) exhaust, it is always advisable to use a heated sample line, especially at a low dilution ratio (see chapter 3.3.3).

5.6. Effect of heating the Dilution Cell

For cold ambient temperatures the heating of the dilution cell and of the hose to the sensor unit is required to avoid water condensation anywhere in the sampling path. The dilution cell is heated to 120°C. This it is hot enough to evaporate tiny droplets (fog) already present in the sample.
For test bed applications with ambient temperatures >20°C, no significant effect of heating the dilution cell has been found. The exhaust temperature in the sampling probe has already cooled down to <50 °C before the dilution cell. Thermophoretic deposition has already occurred, and the re-heating doesn't make any difference.

5.7. Best Practice Summary

The following recommendations may help to minimize errors causing irreproducible results. For a schematic picture of an ideal setup see figure 21 and the end of this chapter.

1) Always use stainless steel probes or pipes in front of the dilution cell or the pressure reducing unit. Mount probes in the upper half of the exhaust pipe, avoid “hanging” installations.
2) The instrument should be placed on position higher than the actual sample point. This prevents water running into the instrument. The sample line should not hang down and form a siphon (water would collect in the lowest point of the sample line).
3) The sample probe should be as short as possible (10-25cm).
4) Do not use any additional transfer lines or very long probes in front of the dilution cell or PRU. This will enforce water condensation and compromise the dynamic response of the device. In addition, time alignment will become very difficult.
5) Use multihole probes only for engine-out sampling in bends at high backpressure.
6) Only use the 2-bar pressure reducing unit at high temperature / backpressure (T>600°C, p>1bar) or if two sample ports are needed (combined sampling with APC). In all other cases use the 1-bar PRU. The latter can even be used for tailpipe sampling, especially when the MSS2 is operated on full sample flow.
7) Clean the pressure reducing unit from time to time and pay special attention to the check valve. Mount the PRU with the check valve pointing downwards. Make sure the PRU is leak tight.
8) Place the dilution cell as close to the sample point as possible (directly attached to probe or pressure reducing unit).
9) Try to avoid unnecessarily long transfer lines (>6m) between dilution cell and MSS.
10) Always use the heated sample line when possible (no space restrictions). For Gasoline applications, especially at dilution ratios DR<5, or for any application when the ambient temperature is below 20°C, the heated sample line shall be used in any case.
11) When using the embedded thermocouple for thermophoretic loss compensation, make sure the thermocouple is inside the exhaust pipe. Don't install it downstream the PRU!

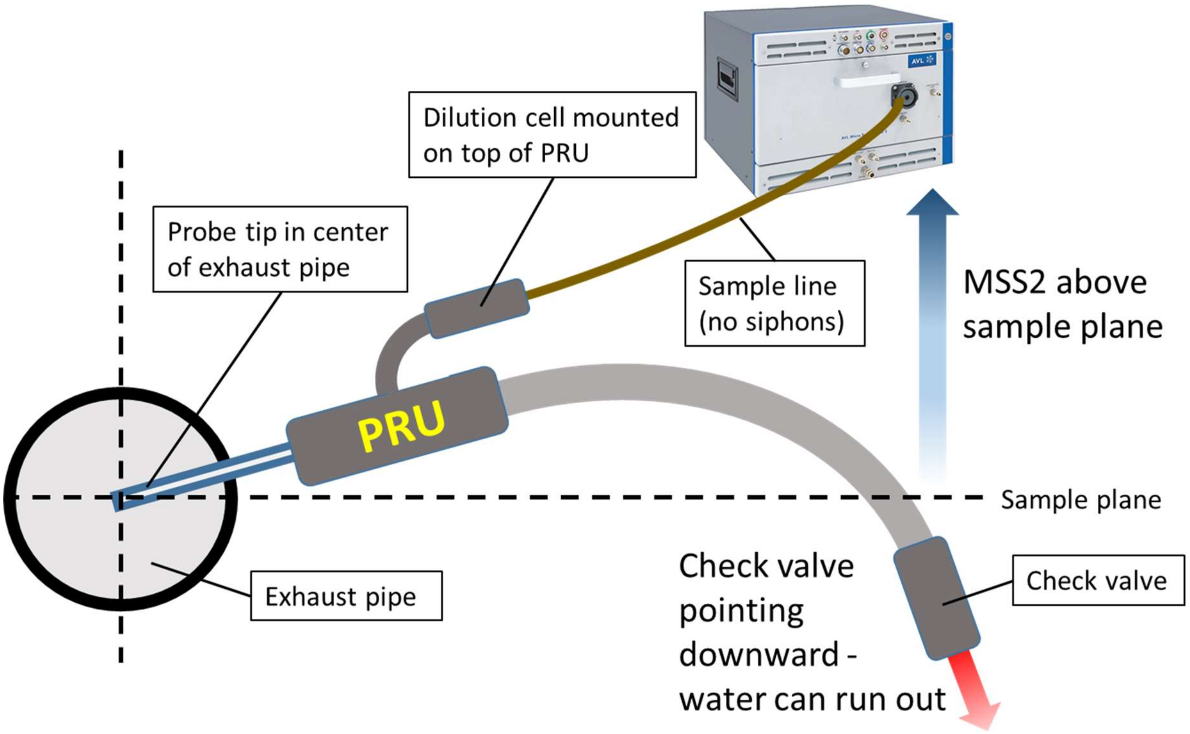
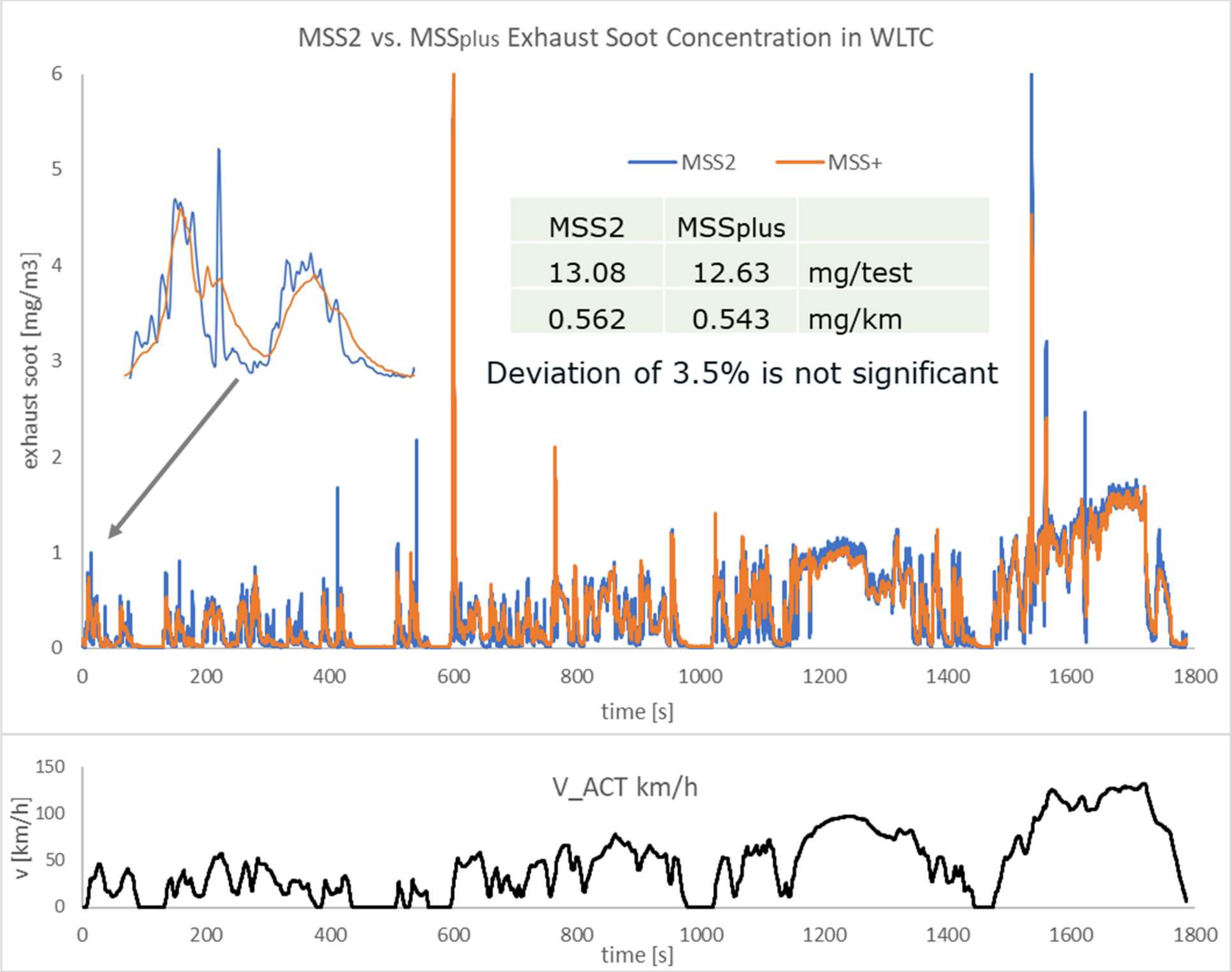


Figure 21: Ideal setup for raw exhaust sampling

6. Comparison to the MSSplus and to other Particle Measurement Methods

Correlation between different instruments or measurement principles are of common interest, especially when introducing a new methodology in order to substitute an existing one. Since the MSS2 shares the same measurement principle and measurement cell with the MSSplus, both generations of instruments correlate perfectly to each other. The agreement between the MSS2 and the MSSplus has been demonstrated during the development of the MSS2. Based on this fact the correlation between the MSS2 and other methods (PM, PN, FSN, etc.) will be the same for all generations of MSS devices. An overview about correlation to other particle measurement methods can be found in the MSS/MSSplus application guide (AU0565) in chapter 7.
The main differences between measurements taken with MSS2 compared to the previous generation devices can be found in the dynamic behavior of transient signals, and not in the agreement between the absolute values. These differences also depend on the sample flow (MSS2 in high or low flow mode) and the used PRU. Figure 22 shows a comparison between MSS2 and MSSplus in a worst-case scenario. The MSS2 was operated with high flow and small (1-bar) PRU, the MSSplus with 2-bar PRU. The backpressure at the sample point was low (<50mbar for most part). The measurement represents a WLTC with a GDI engine. Both devices were operated with dilution DR=5.



MSS2	MSSplus	
13.08	12.63	mg/test
0.562	0.543	mg/km

Deviation of 3.5% is not significant

Figure 22: Comparing MSS2 to MSSplus over WLTC, worst case with low backpresure

Differences can be seen in the faster response of the MSS2 during accelerations. Peaks are higher and show less tailing. However, the integral values over the full cycle are almost identical. This is caused by additional tailing of the MSSplus peaks and averaging effects. The calculated deviation between the two generations of the MSS lies within the normal tolerances. For comparison, the variability of the factory soot calibration is +/-6%, the highest acceptable dilution error at DR=6 is +/-5%, the repeatability of span check is +/-3%.

To summarize:

Differences between MSS2 and MSSplus will show up in the integral result when looking at short dynamic events but will average out over full cycles. This makes cycle data obtained with the MSSplus comparable to those taken with the MSS2.

7. Applications

The Micro Soot Sensor is used in many different applications in Heavy duty and Light duty, as well as large engine, aircraft turbines, fuel reformers and others. The instrument is used for measurements on diesel engines as well as gasoline engines.

This chapter shows some examples of common applications and highlights the specific requirements. All relevant technical aspects for typical diesel and gasoline applications have already been covered in the previous chapters. High-altitude, low-temperature and on-board tests, however, are covered in separate chapters. These applications require some specific precautions on top of the already explained best practice advises.

7.1. Diesel Engines

For all vehicle and machinery types the emission limits are being continuously reduced from the last decades until today and towards the future. The current emission limits can only be fulfilled with quite complex exhaust aftertreatment systems. Whilst the reduction of CO or HC with DOCs (Diesel Oxidation Catalyst) was comparably simple, the NOx/Particulate trade-off remains a challenge for the further reduction of the emissions. A setup containing DOC, DPF and SCR is common for most applications from passenger cars over trucks to non-road machinery.

7.1.1. Aftertreatment Systems with DPF

Since many years a DPF is standard part for most diesel applications. Most MSS applications focus on engine-out sampling upstream the DPF. For calibration and validation purposes the soot mass deposited in the filter is of interest (see also MSS/MSSplus application guide, chapter 8). All relevant information for taking measurements from diesel exhaust is provided in chapter 3, 4 and 5 of this guide. Diesel particle filters need to be regenerated in certain time intervals. A good portion of regeneration (soot is burned off from the filter) is performed continuously during regular vehicle operation (CRT). In cases where this is not possible, a forced regeneration is triggered by injecting additional fuel to increase the temperature inside the aftertreatment system. In some heavy duty and non-road applications this fuel is injected from a nozzle in front of the DOC. In this specific case any sample probe for engine-out measurement must be installed upstream the injection point! If this is not possible, the MSS2 should not sample during regeneration, because high amounts of diesel fuel might be sampled into the measurement cell. This may lead to excessive contamination of the cell.

Modern DPF systems provide a very high filtration efficiency even when empty. The soot concentration at tailpipe is extremely low (below ambient concentration in many cases!). Even though the MSS is capable of detecting very low soot levels (see also MSS/MSSplus application guide, chapter 8), the soot concentration at tailpipe is of minor interest. Exceptions are applications with damaged filters. This can either be failure detection or calibration of OBD PM sensors. The latter requires a DPF with a certain penetration in order to simulate the PM threshold for OBD.

7.1.2. SCR Systems

The main task of the SCR (Selective Catalytic Reduction) system is the reduction of NOx emissions. Engines with a DOC produce significant amounts of NO_2, which may require an SCR system for further treatment.

Basically, the Micro Soot Sensor is capable of sampling behind an SCR system. If the SCR is not working at the best performance (during development), aggressive by-products like amines, ammonia (NH_3) or excess urea may be present in the exhaust. Thanks to the dilution system, the

MSS2 is relatively robust against such exhaust components, the device should be carefully monitored for contamination though. If urea gets into the measuring cell of the device, it may cause serious damage to the instrument. Sampling in front of an SCR is only possible upstream the urea injection point. Sampling behind the urea injection nozzle must be avoided! In any case the heated sample line shall be used and a DR>6 is highly recommended.

7.2. Gasoline Engines

Due to the very high sensitivity of the MSS2, it can be used for measurements on GDI (Gasoline Direct Injection) engines (see also MSS/MSSplus application guide, chapter 8). The mechanism of soot formation in a GDI engine is comparable to diesel engines, but the high hydrogen content of the fuel leads to a higher amount of water vapor in the exhaust. All relevant information for taking measurements from gasoline exhaust is provided in chapter 3, 4 and 5 of this guide.

7.2.1. Gasoline particle filters

Gasoline particle filters are required for most modern GDI engines to meet the stringent particle number limits under RDE conditions. With such filter system the requirements for soot measurements become very similar to diesel engines. For calibration work engine-out sampling upstream the GPF is required and using the PRU is mandatory. Even though the backpressure is lower than in diesel applications, the exhaust temperature is much higher. Therefore, special attention should be paid for potential damage of the Viton O-rings sealing the check valve (see chapter 5.4).

7.3. High-Altitude Testing

High-altitude applications gained additional importance over the last years. This development is mainly driven by an extended RDE and in-use compliance legislation in many countries. Development work is mainly performed in a simulated environment (altitude chamber or ACS) whereas compliance testing is carried in out in real-world (PEMS testing). The MSS2 can cover all three use cases. This represents a key difference compared to the previous generations of the Micro Soot Sensor. The first generation MSS was specified to altitude applications up to 2000m under stationary conditions. The same applies to the MSSplus. However, with firmware version 3.05 or higher, the MSSplus offers dynamic altitude compensation for the measurement signal. This allows for uphill and downhill driving during ca continuous measurement.

The MSS2 does not have any of these restrictions. It offers an operational range from -200m to 5000m relative to sea level including dynamic compensation. For altitudes above 3000m a secondary pump is required (MSS2 product guide, chapter 11.3)

The MSS2 uses the same algorithms for altitude compensation as the previous device generations. This makes measurements taken with MSS and MSSplus (up to 2000m) directly comparable to MSS2 measurements. Figure 23 shows the altitude compensation of the MSS over the whole range. The measured soot concentration was normalized to 1mg/m3. Over the whole range a maximum deviation of +/-4% was observed.

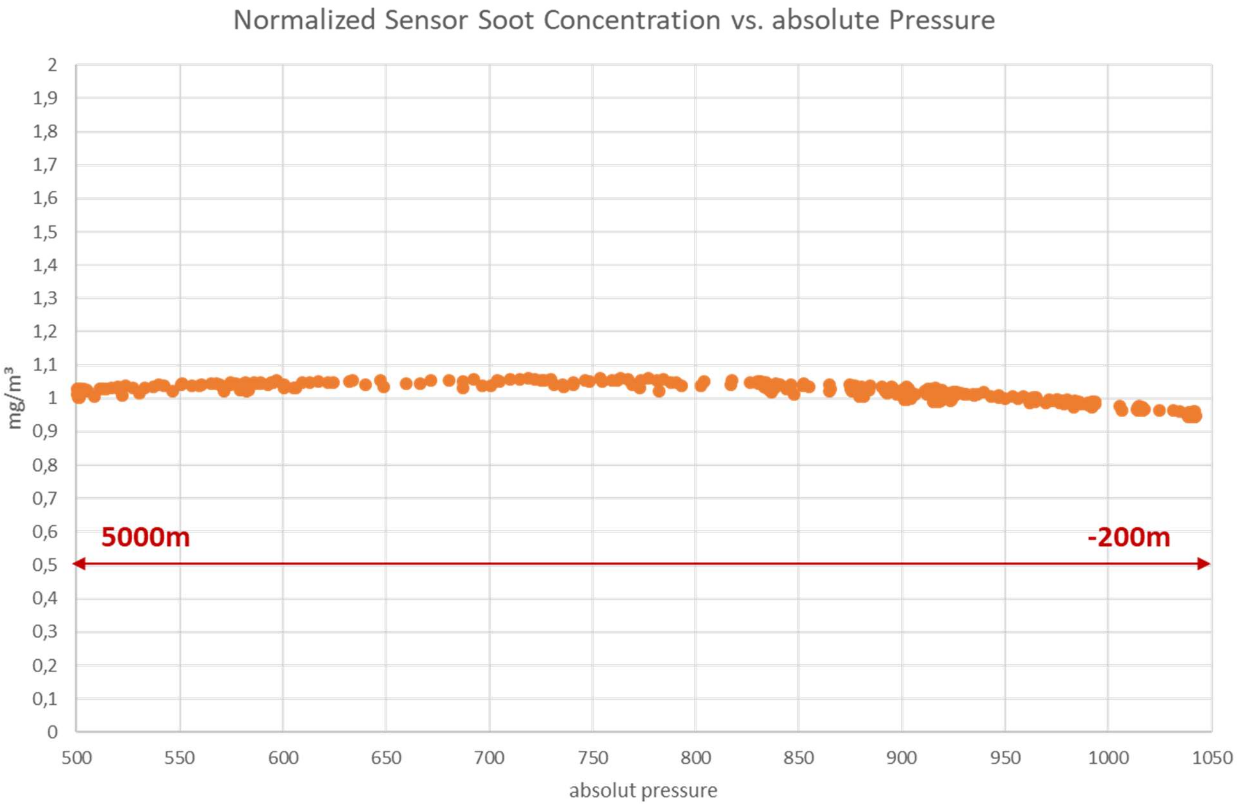


Figure 23: Normalized soot concentration measured by the M22 between -200m and 5000m

Sometimes high-altitude testing is combined with low temperature. In this case all recommendations from chapter 7.4 apply.

7.3.1. Testing inside an Altitude Chamber or On-board

For the altitude chamber no specific pre-cautions need to be taken, if the device is placed inside the chamber. This is the typical use case anyway, because it is very difficult to route sample lines to the outside of the chamber without creating major leaks. The same applies for tests in moving vehicle. For the MSS2 it does not make any difference if the altitude chamber gets evacuated or the device is carried uphill in vehicle. For the specific requirements regarding on-board applications, see chapter 7.4.
Figure 24 shows the exhaust soot concentration measured in engine-out position of a diesel engine. The test has been conducted in an altitude chamber at 3500m altitude to demonstrate the capabilities of the MSS2. The instrument was using the secondary pump unit and was operated with the high flow setting (because of a relatively long probe, see chapter 3.2.5). The sample point was upstream a DPF. This kind of measurement would not have been possible with an MSSplus.

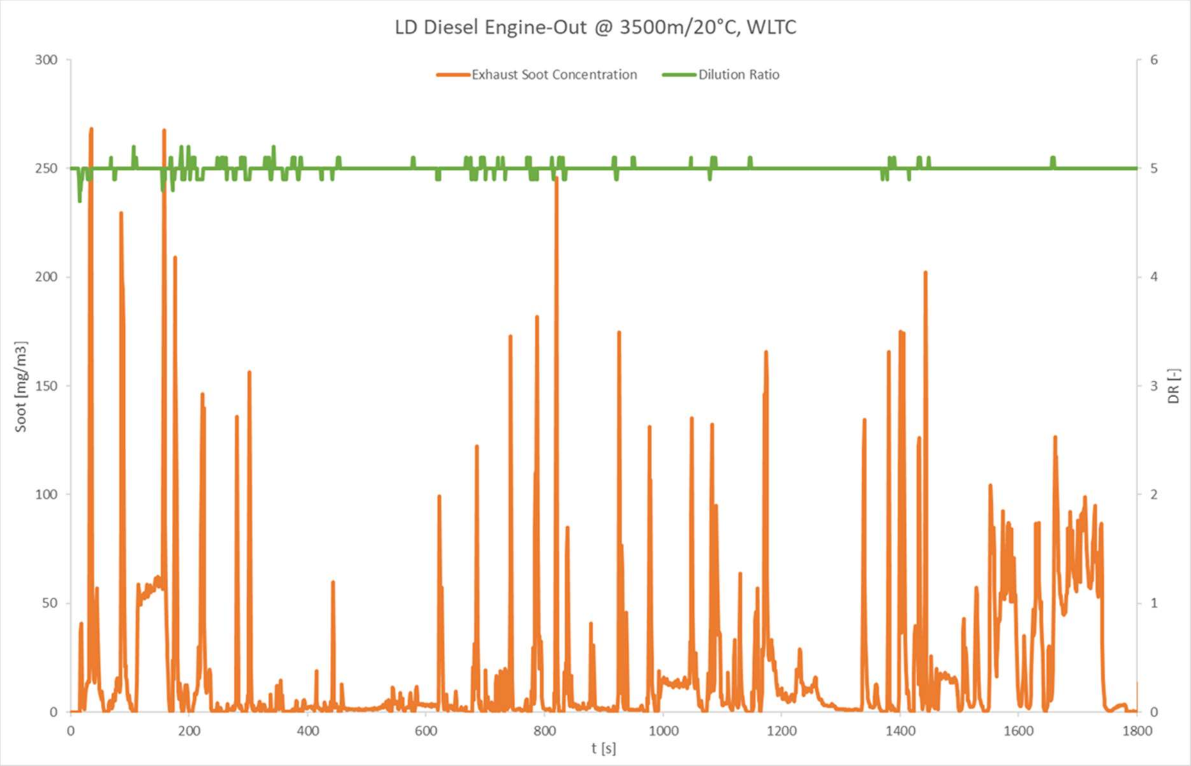


Figure 24: WLTC at 3500m, measured with MSS2

Figure 25 shows an example of a dynamic altitude test using the same vehicle setup as in the previous example. Here a car rolling downhill in idle was simulated in the altitude chamber. Similar tests could be performed on-board by driving on mountain roads. This is possible because of the dynamic altitude compensation of the MSS2.

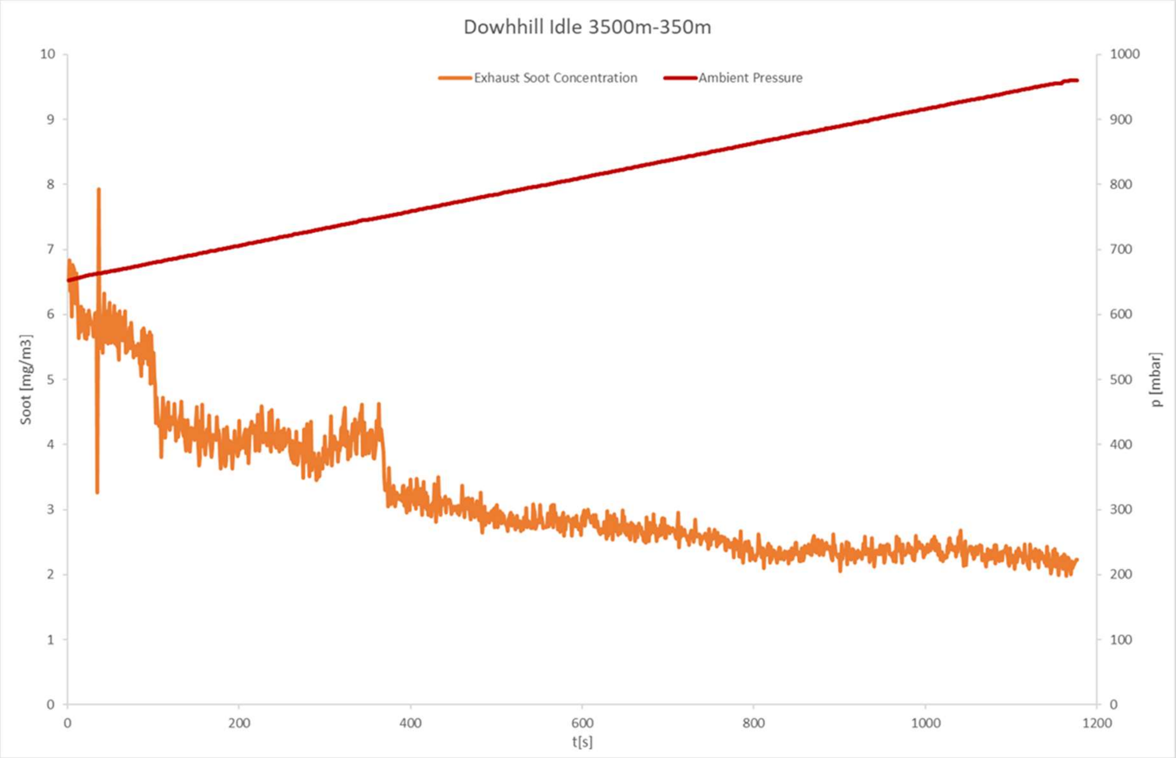


Figure 25: Diesel vehicle idling downhill from 3500m to 350m

7.3.2. Altitude Simulation with Air Conditioning Systems (ACS)

In most engine development tasks altitude is simulated by using an air conditioning system (ACS). An ACS can evacuate the air inlet and the exhaust stack of a vehicle while the UUT is operated under the normal ambient conditions of the location. Even though such a simulation setup has a lot of advantages (faster, easier, less costs) compared to a full altitude chamber, it creates some specific challenges for exhaust measurements. Like the engine itself, the measurement device is placed in an area of local ambient conditions, whereas the pressure conditions at the sample point can be very different. If a sea level simulation is performed, there will be a slight overpressure inside the exhaust duct. In such case a standard setup with PRU is required. Figure 26 shows a schematic ACS setup.

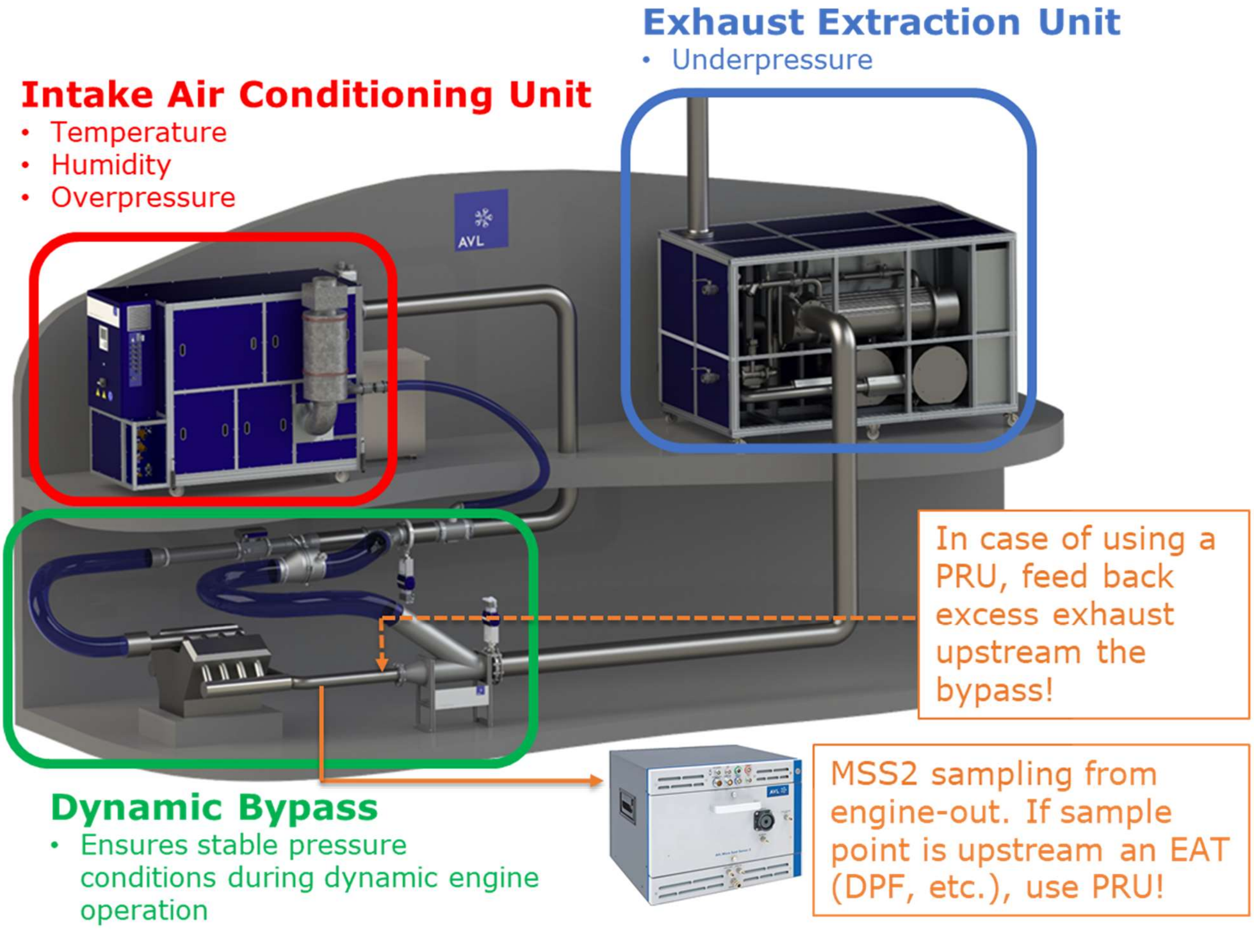


Figure 26: Schematic ACS setup (AVL)

In case of high-altitude simulation some specific precautions for the setup must be taken:

- The whole setup with sample line and PRU must be as leak tight as possible. The leak rate of an external leak check including the PRU should be not higher than <6mbar*l/min.
- If the PRU is installed at an engine-out location used, the excess exhaust leaving the check valve must be fed back into the controlled altitude environment. This must be a location behind the tailpipe. In case of the AVL ACS (figure 23) the location must be upstream the bypass.

- For tailpipe sampling locations no PRU should be used. Note that some ACS systems generate significant pressure pulses during transient cycles due to delays in pressure control. This may impact the dilution performance (dilution gets a bit more unstable, see also chapter 3.2).

For the photoacoustic sensor itself and the implemented altitude compensation there is no difference between ACS and altitude chamber application.

7.4. Low-Temperature Applications

Natively the MSS2 is specified to work at temperatures down to -10°C. Even though the device can be switched on at -10°C, it is advisable to pre-heat the device by switching it to PAUSE in a warmer environment. This saves a lot of time and energy. If this is not possible and the device is switched on at a temperature below 0°C, a pre-heating procedure is performed before the device can change into any regular operation state (HBERNATE – PAUSE – STANDBY). This pre-heating time increases depending on temperature. It starts from no pre-heating for temperatures >0°C and takes 55 minutes at -10°C. For additional details on low temperature operation and the warm-up procedure see MSS2 user guide, chapter 4.12.

As already mentioned in previous chapters, water condensation is a big issue and must be prevented as best as possible. A heated sample line must be used in any case! Low-temperature applications add an additional problem, which is the formation of ice. Any water collecting in unheated areas of the sampling system (probes, PRU, etc.) can potentially freeze and block the gas flow. The check valve of the pressure reducing unit is the most critical part, since it is one of the coldest spots in the setup and exposed to high humidity. Any ice formation will cause either leakage or congestion. To prevent the issue of ice formation, the whole unheated area in front of the dilution cell should be kept at >0°C as long es exhaust is sampled. This can be achieved by a achieved by careful placement in areas with certain heat radiation, additional insulation and application of heated tapes or sleeves. Any water must be removed out of these parts before and after test runs. Therefore, multiple purges should be performed before and after each test. Note that he MSS2 must be connected to dry shop air to enable this feature (MSS2 product guide, chapter 3.5.1.5).

Check list for low temperature applications:

- Place device and sample lines protected from air blowers (avoid windchill effect)
- Connect the MSS2 to dry shop air, if possible. This enables the purge function.
- Keep the unheated parts of the sampling setup (probe, PRU, dilution cell inlet) above 0°C, at least while the test is running
- Always use the recommended setup from chapter 5.7 (figure 18)
- Relieve excess flow from PRU check valve into an open volume or a heated hose to prevent congestion by ice
- Don’t use the PRU in tailpipe applications. Use a short standard probe (10-15cm) facing downstream.
- Apply multiple purges before and after every test

For working at temperatures even lower than-10°C, the climate kit for the MSS2 should be used. The kit consists of a trolley with an integrated climate control, a sample line with an extended temperature range (-30°C instead of -10°C) and a heated jacket for the pressure reducing unit. The trolley also contains a second power supply unit for powering the heated jacket for the PRU and an additional tail pipe sampling kit (If used with an AVL APC sampling from the second port of the PRU). The whole setup offers maximum safety for all applications below 0°C.

Even though the kit is designed to fit the 2-bar PRU, it can also be used together with the smaller 1-bar PRU of the MSS2. The check valve at the exhaust outlet of the PRU is heated as well.

For more details about setup and operation please see the climate kit user guide (AU6039). Additional application notes for this kit are available in chapter 3.2 of the user guide.

7.5. On-Board Measurements

Measurements on the road are well known from PEMS applications. These applications target the demonstration of compliance during real-world use of a vehicle (e.g. RDE or HDIUT). The MSS2 has been designed for on-board use, but it is targeting different applications. Most typical use cases are engine calibration work and optimization of the exhaust aftertreatment strategy (e.g soot loading in DPF/GPF). Many of the applications for diesel and gasoline engines listed in the previous chapters, can be performed on the road (to a certain degree).

On-board applications are one of the biggest strengths of the MSS2. It has been designed for easy installation in a vehicle and fully fits into the AVL MOVE iS system. There are various options for mounting systems for the inside or the outside of a vehicle, see MSS2 product guide, chapter 4.6. The MSS2 features a CAN bus interface, which allows the direct connection to an AVL MOVE EFM. This enables to assess specific soot emission results (total over test) in a stand-alone setup without access to any vehicle data or additional components for data acquisition from multiple devices. The EFM is connected directly to the CAN port of the MSS2 by using a specific cable. The exhaust flow is recorded into the standard measurement data logfile together with the concentration values. This makes data processing easy. Another option is to connect the CAN interface with ETAS INCA. All relevant data from the MSS2 (including EFM, if connected) can be logged together with data from the ECU and other sensors into one data file. For proper communication with INCA a DBC file is needed. This is a simple test file describing the structure of the transferred data and is available from AVL. Figure 27 shows a real-world setup for an on-board test in a diesel passenger car. The MSS2 is mounted on the passenger seat console. The probe is installed at engine-out location upstream the DPF an guided through a hole into the passenger footwell. Due to the DPF location, a quite short probe could be used. The RPU is installed inside the car. The MSS2 is connected to an ETAS INCA system for data acquisition.

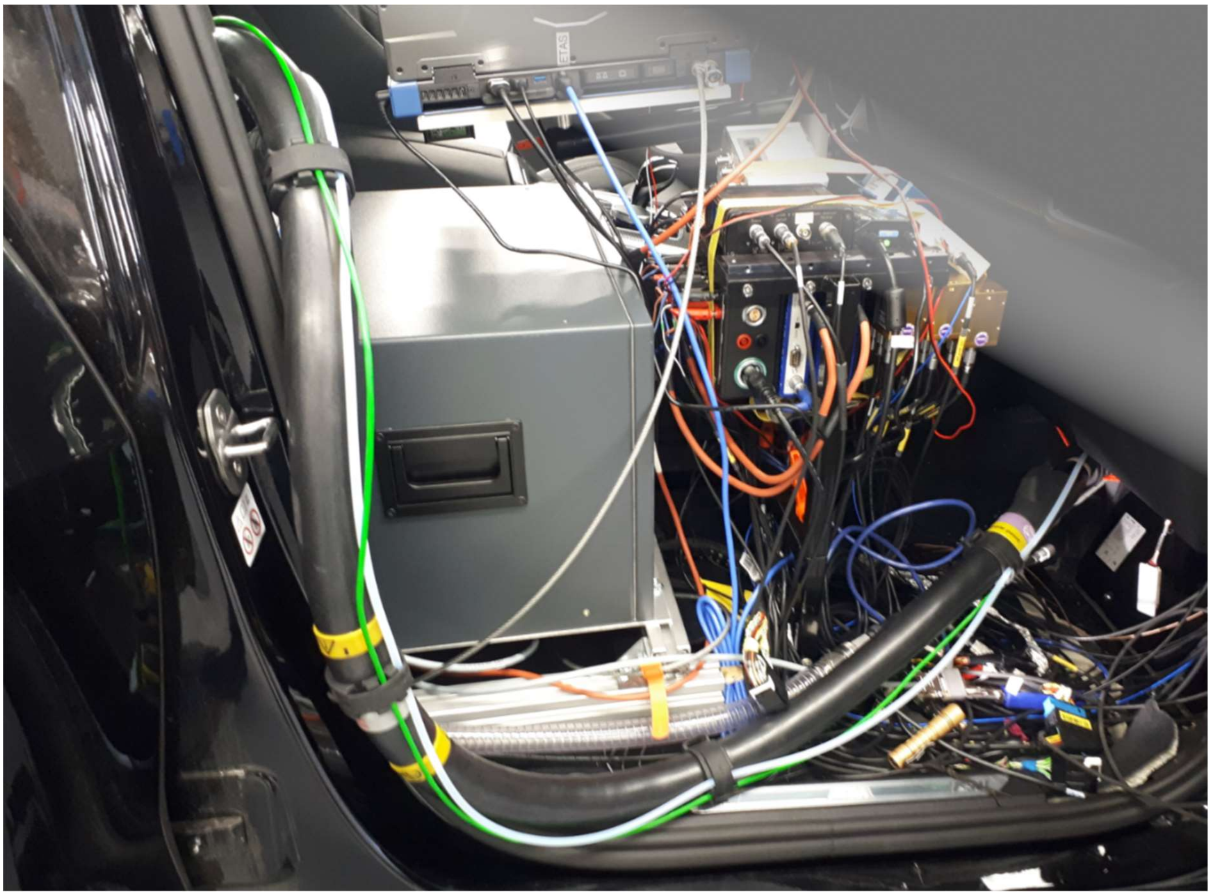


Figure 27: MSS2 installation in a passenger vehicle

8. Abbreviations

GDI:	Gasoline Direct Injection
ACS:	Air Conditioning System
PRU:	Pressure Reducing Unit
PM:	Particulate Matter
CVS:	Constant Volume Sampler
EFM:	Exhaust Flow Meter
EAT:	Exhaust Aftertreatment
GFM:	Gravimetric Filter Module
MSS:	Micro Soot Sensor
MSS^{plus}:	Micro Soot Sensor Plus
MSS2 :	Micro Soot Sensor 2
APG:	AVL Particle Generator
DPF:	Diesel Particulate Filter
GPF:	Gasoline Particulate Filter
DOC:	Diesel Oxidation Catalyst
LNT:	Lean NOx Trap
SCR:	Selective Catalytic Reduction

CRT:	Continuously Regenerating Trap
EGR:	Exhaust Gas Return
NEDC:	New European Drive Cycle (Light duty)
ESC:	European Stationary Cycle (Heavy duty)
PMP:	Particle Measurement Program
HDIUT:	Heavy Duty In-Use Testing according (US EPA)
TOT:	Thermal / Optical transmittance
CAST:	Combustion Aerosol Standard
MFC:	Mass Flow Controller
ACS:	Altitude Control System
UUT:	Unit under Test
RDE:	Real Driving Emissions
ECU:	Engine Control Unit