COMPARATIVE STUDY ON PRESSURE DROP OF VARIOUS AIR FILTERS

LAST MODIFIED: 12TH APRIL 2016 (BY SJM)

AIM OF THE MEASUREMENT

The main aim of the lab session is to compare various (at least 4) air filters that are used in the same passenger car. Usually wide range of air filters of various types can be used as replacement filter of the factory air filter in a passenger car. Except the so-called "*sport*" (*racing*; *high performance* etc.) air filters the replacements filters are very similar in construction to the factory filter, but there may be a huge difference in their prizes.

The question „Which air filter is to be chosen as replacement filter?" is usually not an easy task to answer. The lab session aims to determine the pressure loss characteristics of the filter that is one of the most important parameters. Comparison & evaluation of the filters will be performed by measuring the filter pressure loss ($\Delta p_F'$) vs. volumetric flow rate (q_V) of the air. The measured $\Delta p_F' = f(q_V)$ characteristic curves for each filter can be compared and analysed.

Filter pressure loss is calculated by measuring the upstream and downstream pressures.

$$\Delta p'_F = p_{F,\text{upstream}} - p_{F,\text{downstream}}$$

The ξ_F filter loss coefficient is the ratio of the pressure loss and the dynamic pressure.

$$\xi_F = \frac{\Delta p'_F}{\frac{\rho}{2} \cdot v_{REF}^2} = \frac{p_{F,\text{upstream}} - p_{F,\text{downstream}}}{\frac{\rho}{2} \cdot \left(\frac{q_V}{A_{REF}}\right)^2}, \text{ where}$$

ρ [kg/m^3] : air's density (ideal gas law using ambient pressure p_0, and temperature T_0)

v_{REF} [m/s]   : reference velocity, (! differs from the filtration velocity, v_F)

A_{REF} [m^2]   : reference (projected) free cross section of the filter, $A_{REF} = A \times B$, where A:width, B: length

Filter pressure loss and loss coefficient are to be investigated at least for 4 different filters. The measured and calculated quantities are to be plotted in common diagram as comparison graphs. 7 air filters made by different companies are available: 6 „normal" and 1 „sport" filter, at least 2-2 pieces of each.

PASSENGER CAR DATA

Type: BMW 318iS (E30) 1990/01
Engine code: M42B18
Engine data: 1796 cm^3, 4 cylinders, 16 valves, DOHC
Power: P_{max}= 100 kW / 136hp @ 6000rpm
Torque: M_{max}=172 Nm @ 4600rpm
Rotational speed: n_{idle}= 850±40 rpm
                     n_{max}= 6500±40 rpm
Air flow meter: Bosch 0280202203
Electronic control: DME M1.7 (Motronic)

WHY DO WE NEED AIR FOR THE ENGINE?

The most efficient burning process of the fuel the given stoichiometric ratio (λ=1) of air / fuel is a must. This is calculated by the MCU (Motor Control Unit) and by the DME (Digital Motor Electronic), performing in-time control of the fuel „injection timing", depending on the intake air flow rate.

The intake air is flowing through the air filter. The flow rate varies between minimum and maximum flow rates that are determined by the idle and maximum rotational speed of the engine's main shaft.

By moving the accelerator pedal, the driver of the passenger car varies the intake air duct's butterfly vale's position (from closed to fully open).

The flow rate of the intake air is to be measured very precisely.

The intake air's mass flow rate (q_m[kg/s]) is measured by AFM (Air Flow Meter). DME regulates the injected fuel and the injection timing based on the signal of the AFM, the signal of the butterfly valve (accelerator pedal) and main shaft position etc. /Regulation process uses the „*injection map*" that was measured by the car manufacturer./ For intake air mass flow rate the intake air's temperature is needed to measure. AFM contains also a heated film probe for the present set-up.
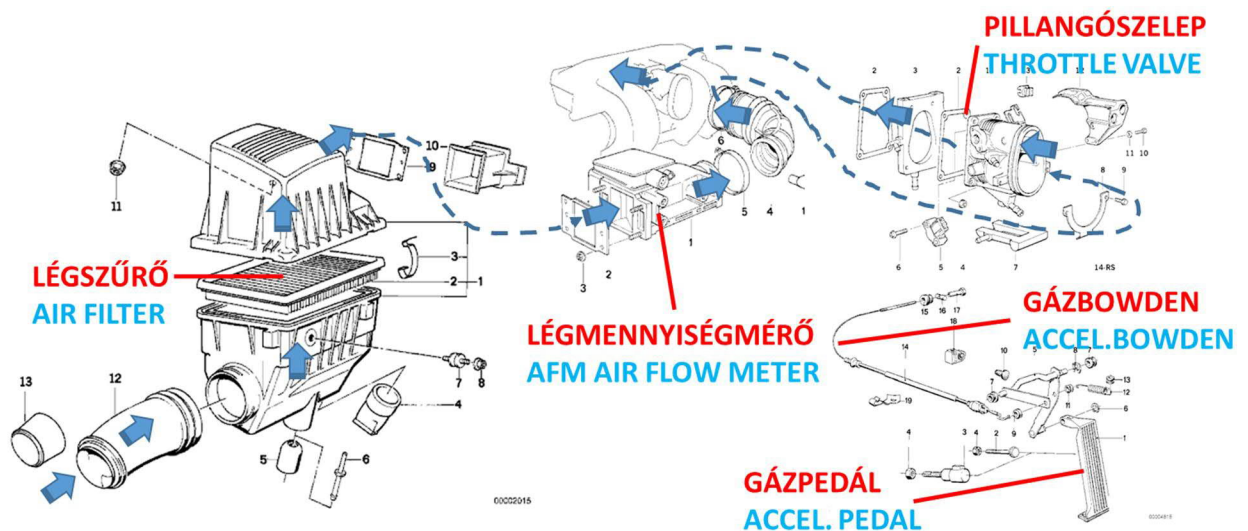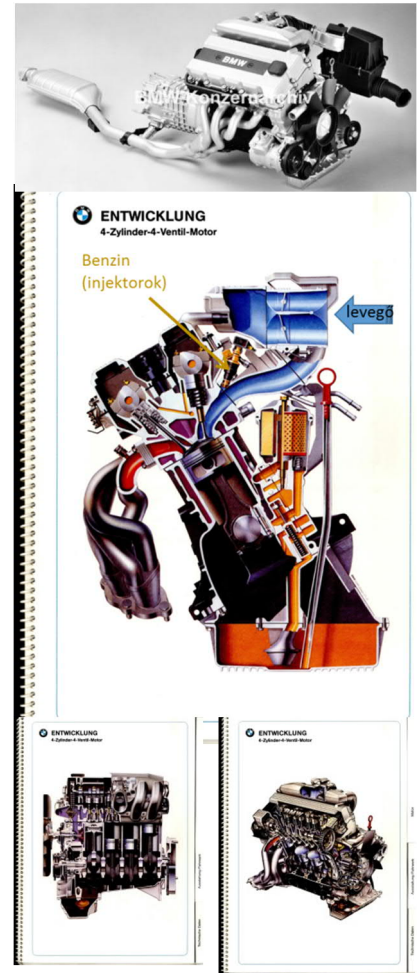
WHY DO WE NEED AIR FILTER?

Primary aim of using air filter is to separate particles from the intake air. Particles (solid / liquid contaminants) may cause severe injuries in the engine (e.g. corrosion, pluggage, congestion). It is worth to mention, that there are special air filter housings for e.g. African markets that contain an additional cyclone pre-separator in the lower housing upstream of the panel air filter to separate the larger/heavier particles from the intake air, hence unloading the main air filter.)

Using air filter aims a particle separation for all particle size ranges with a highest possible efficiency. The $\eta(d_p)$ fractional efficiency of the filter is preferable as high as possible for in the whole rpm-range of the engine. This efficient separation process cannot be performed without a pressure loss. Minimizing this pressure loss of the air filter means minimizing the intake power losses of the engine.
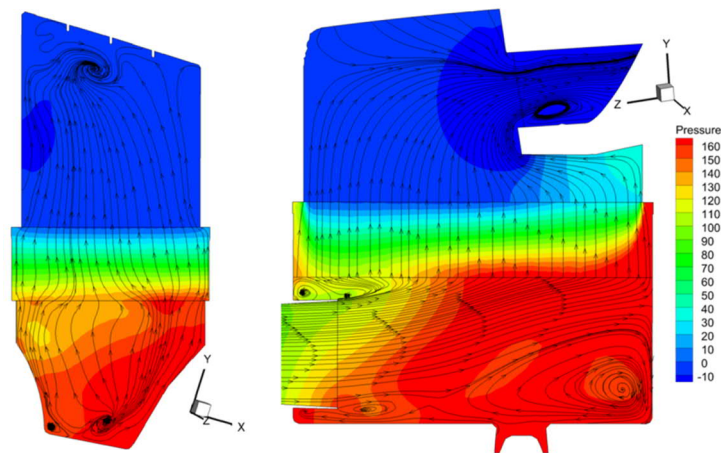
Pressure distribution contours and streamlines in two mid-planes of the filter housing (CFD result)

Generally, the higher the fractional efficiency and the less the pressure loss, the better is the filter performance at the given engine rpm.

Unfortunately, the air filter manufacturers usually do not inform the customers about these important parameters of the air filters. Mainly, other manufacturers' comparison graphs or advertisements of sport air filters can be found only, see e.g. these diagrams below.
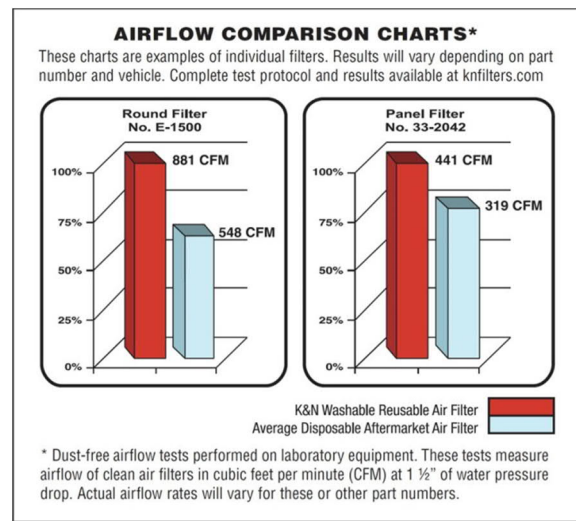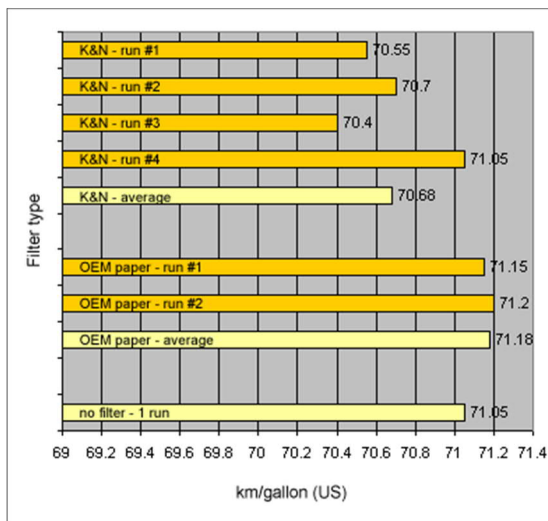
Besides efficiency and pressure loss also other parameters (prize, lifetime, particle loading capacity, cleaning, normal / racing application purposes) may guide us when selecting the replacement air filter for our passenger car.

CONSEQUENCIES:

Due to the pressure loss (Δp_F') – possible only a very small – part of the engine's power (P_{motor}[W]) is lost. The P_F[W] filter power loss can be calculated for each point of the Δp_F'=f(q_V) characteristic curve:

$$P_F=\Delta p_F\text{'} \cdot q_V$$

The engine's *rpm*-dependent power curve P_{motor}=f(n) for the present passenger car is known (see the scanned diagram later). We can calculate P_{rel}[%]relative power loss: i.e. the ratio, that shows us how many percentage of the motor power is lost due to the air is flowing through filter.

$$P_{rel}=P_F/P_{motor}$$

Therefore, the P_{rel} =f(n) characteristic curve can also be calculated and plotted for each filter.
The flow rate of the intake air is determined by the *rpm*-range of the engine ($n_{idle} \leq n \leq n_{max}$), hence for given n we can measure the intake air flow rate q_V and filter pressure loss Δp_F'.

Note, that at air intake flow rates corresponding to n< n_{idle} , i.e. below idle speed (n_{idle}) we are not interested in the filter's power loss data, since usually we do not drive out car below idle speed.
Note also, that comparison for sport's filter is more important at around max. rev. limit! (n_{max})
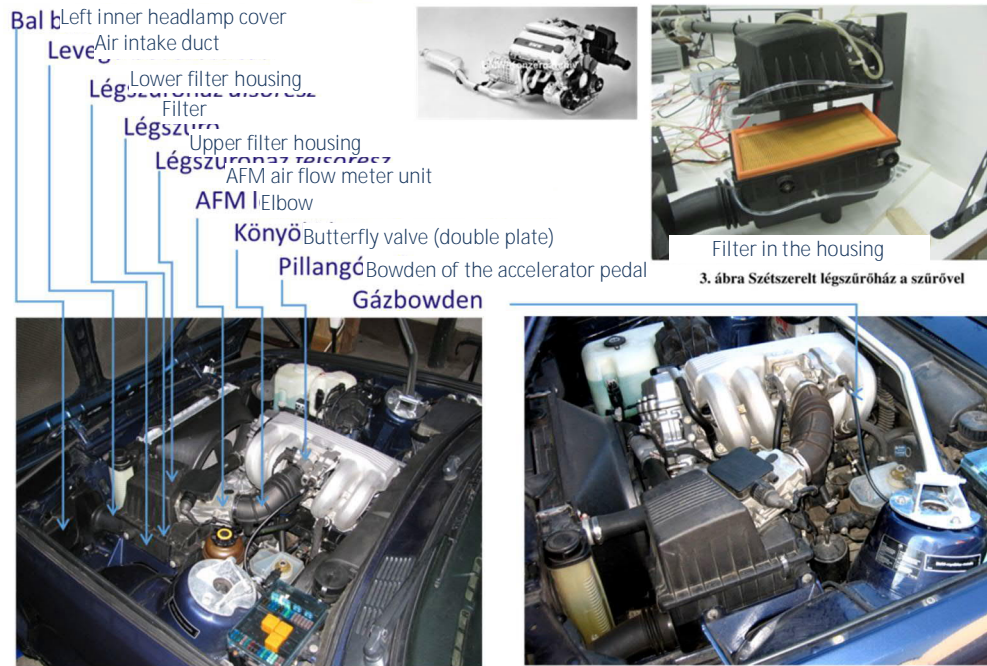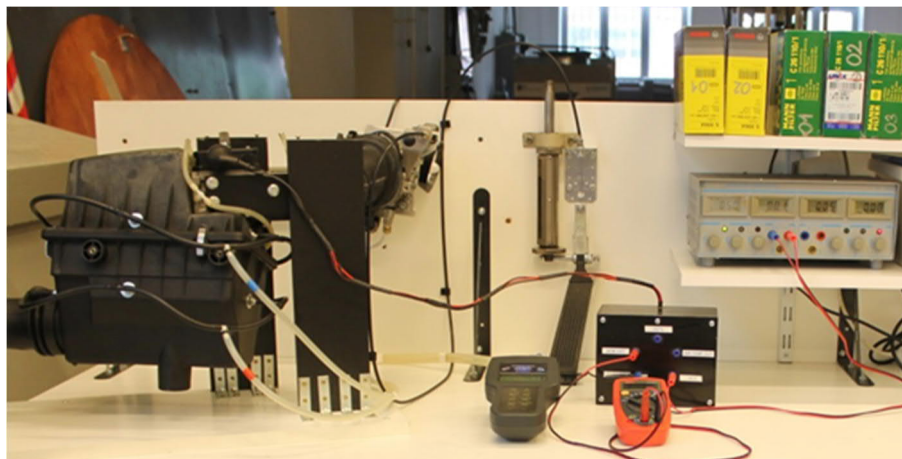
EXPERIMENTAL SET-UP

The laboratory model set-up is a M=1:1 scale-model of the real set-up.

The measurement set-up contains the same factory elements that are used in the real passenger car. **Please take care of the original factory parts of the set-up!**

The engine's air intake as volumetric flow rate is produced by a radial fan. The fan's suction side is connected to the butterfly valve of the set-up, see on photos below.

Bal b — Left inner headlamp cover
Leve — Air intake duct
Lég — Lower filter housing
— Filter
Légszűr — Upper filter housing
Légszűronaz — AFM air flow meter unit
AFM l — Elbow
Könyö — Butterfly valve (double plate)
Pillangó — Bowden of the accelerator pedal
Gázbowden

Filter in the housing

3. ábra Szétszerelt légszűrőház a szűrővel

The figure below shows the photo of the measurement set-up. The filter housing is on the left (lower & upper filter housing), that contains the air filter. Please take care of the clamps that fix the upper/lower housings to each other! Also take care of the pressure 4-4 taps upstream and downstream on the filter housing! The set-up is connected to the radial fan's suction side with rigid tubing. The parts of the set-up in streamwise direction: air enters from the ambient through the intake circular, flexible rubber duct to the lower filter housing, than flows through the air filter, entering the upper filter housing. The air flow leaves the upper housing through an inlet guide towards the AFM. Downstream of the AFM is the double-plate butterfly valve, and the circular duct towards the suction side of the radial fan.

Experimental facility for filter pressure loss measurement

After switching on the fan (running on full power, without the fan's *rpm* regulation) the air flow rate can be regulated only via opening/closing the butterfly valve of the set-up with moving the accelerator bowden of the accelerator pedal – as it is done by the driver in the reality, too. Valve position between fully closed and fully open valve plate corresponds to approx. l_{max}=50-55mm length of the bowden cable. Note, that for the precise measurement the bowden cable length setting is to be performed in steps of using $\Delta l = 1$mm or 2mm!
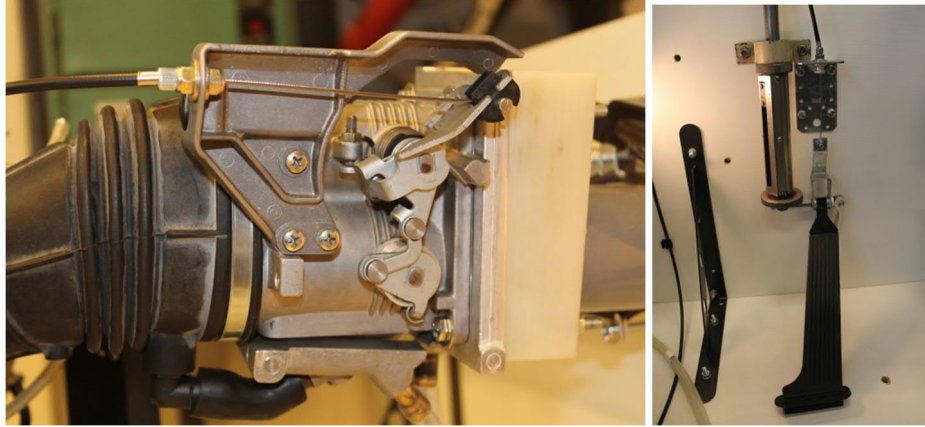

Double valve butterfly valve (left), accelerator pedal with manual bowden setting (right)

The air flow rate can be measured by the AFM made by BOSCH GmbH. The AFM contains a turning plate (see sketch below) that turns due to the pressure difference in the AFM and it's very stable angular position is measured electronically (AFM's output voltage signal), and also can be read on the protractor. The flow rate corresponding to the angular position was calibrated previously to a standard orifice plate.
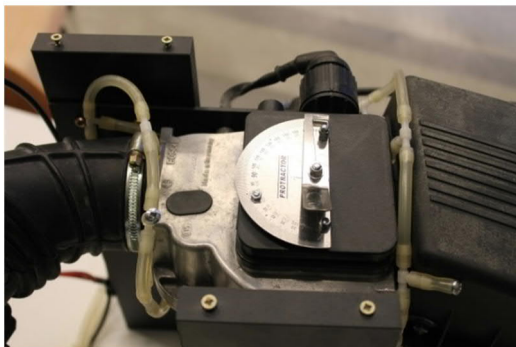

AFM with outer angular setting scale
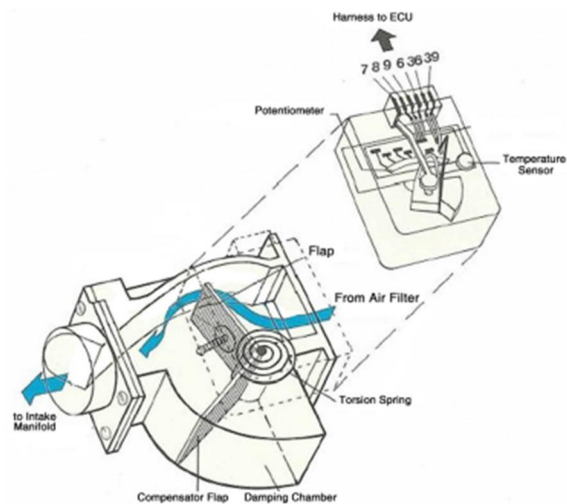
The AFM is supplied by constant 5.0V by a laboratory DC power supply ("+5V" ; "GRND"). Note, that the supply voltage mustn't differ from the constant 5.0V setting! (It is needed to check it regularly visually.) One of the AFM's output signals is to be measured: $U_{AFM,out}$ [V], that corresponds to the plate angular position (α). The α can be read visually on the protractor, while it is measured also by the multimeter: the output voltage signal ($U_{AFM,out}$=0.000 ÷ 5.000V) is measured by the multimeter. Both are needed to be recorded, but for the calculation only the voltage signal $U_{AFM,out}$ [V] is to be used.

**Please, do not even think about to touch the angular indicator's needle!**
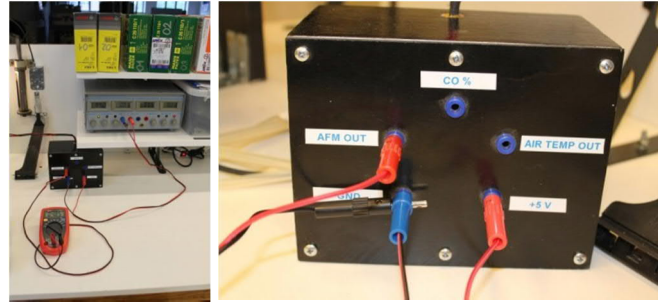
AFM's power supply and connector box („+5V";"ground") and output signal („U AFM,out")

The flow rate corresponds to the angular position that was calibrated previously to a standard orifice plate. Based on α or on $U_{AFM,out}$ the volumetric air flow rate can be calculated.
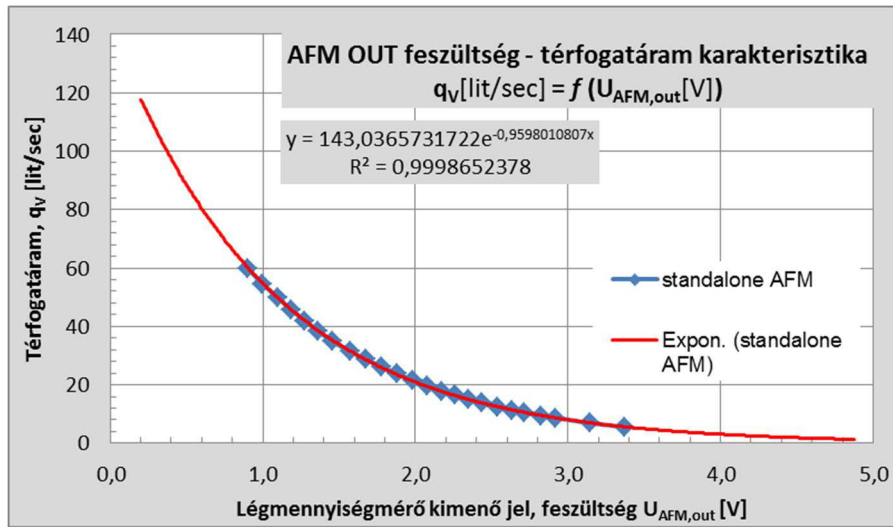
AFM's calibration curve, $q_V = f(U_{AFM,out})$

The fitted trendline's equation $\qquad q_V = 143{,}0365731722 \cdot e^{-0{,}9598010807 \cdot U}$ is to be used to calculate q_V [liter/sec] from voltage signal. Note, that q_V results in litres / seconds! During the lab session $\alpha[°]=f(\mathbf{U_{AFM,out}})$ curve is to be plotted for checking the measurement. Fully closed position corresponds to $\alpha=0°$ (see inner scale of the protractor!) Compare your own measurement results to the previously measured one! (see diagram below, the $\alpha[°]=f(U_{AFM,out})$ curve must be fully linear!)
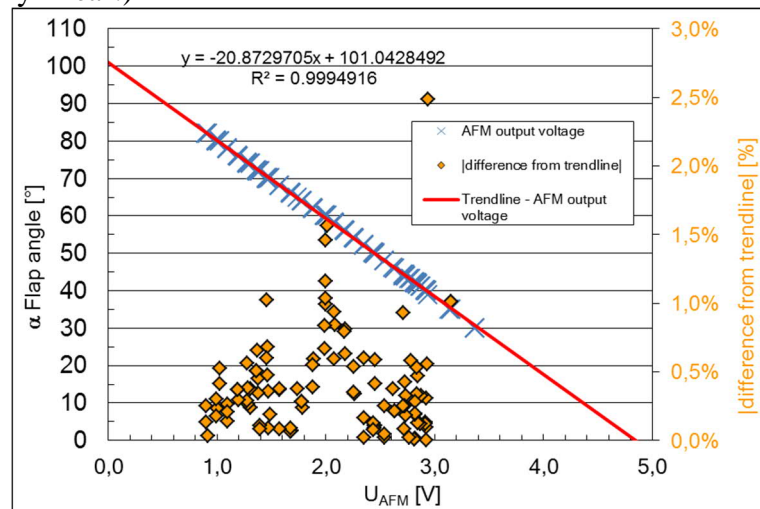
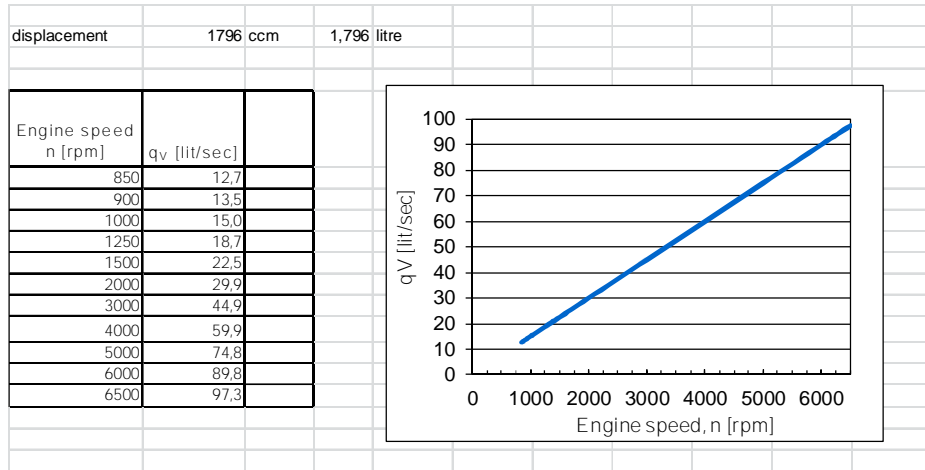AFM's calibration curve, $\alpha=f(U_{AFM,out})$

INTAKE AIR FLOW RATE

It is needed to know how many intake air flow rate corresponds to given engine's rpm. While assuming 100% volumetric efficiency of the engine the volumetric flow rate of the intake air can be calculated using the engine's data (DOHC, 4 cylinders, 16 valves, $V=1796cm^3=1,796liter$):

$$q_V \text{ [liter/sec]}= 0,5 \cdot V\text{[liter]} \cdot (1/60) \cdot n \text{ [rpm]}$$

NOTE: The equation above results in q_V [liter/sec]; while using V[liter] and n [rpm]!
The *rpm*-range between idle and maximum engine speed can be plotted, too, see diagram below.

displacement	1796 ccm	1,796 litre

Engine speed n [rpm]	q_V [lit/sec]
850	12,7
900	13,5
1000	15,0
1250	18,7
1500	22,5
2000	29,9
3000	44,9
4000	59,9
5000	74,8
6000	89,8
6500	97,3

ENGINE's POWER CURVE

P_{motor}[kW]=f(n[rpm])

The power and torque curves for the present car's engine are known only in scanned form. P_{motor}[kW] for the given n[*rpm*] can be read from the diagram. Calculating the filter's power loss (P_F) and

$P_{rel} =P_F/P_{motor}$ [%]

will result in the filter's relative power loss curve: $P_{rel} =f$(n).

Note, that power curve point at idle speed of n_{idle}=850rpm can be only linear extrapolated.
The radial fan can supply air flow only up to the mid-range of the power–curve. Although it isn't linear, but a linear trendline can be fit to the whole power curve that allows for easy calculation.
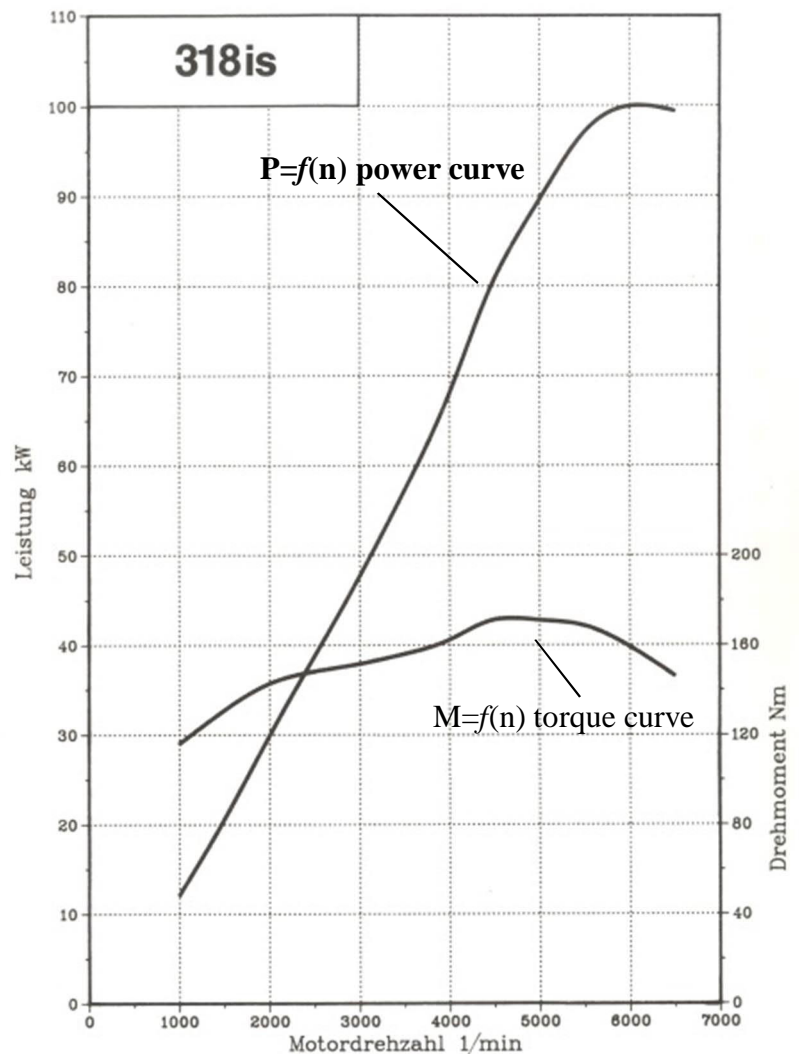
AIR FILTERS AVAILABLE FOR LAB SESSION TESTING

Filters: The „original" factory air filter's part number is BMW-13721715881, it's prize this year 7846.-HUF+27%VAT = ~32.-EUR. (This is sold only at official BMW dealers, but it is well known that the BMW GmbH isn't itself a filter manufacturer). Besides the "factory" OEM (Original Equipment Manufacturer) filters there are several replacement air filters'

manufacturers / distributors exist, who may sell air filters for the same type of car. „*Which one to choose?*" is a question that usually the car driver cannot simple answer since their construction & outlook are very similar. Except the sports air filter's outlook are quite different. Filter's weight, numbers of lamels or their prizes, quality–feel may vary a lot. For the present lab session 7 different filters, 2 pieces of each are available. At least 4 filters of your choice are to be measured. All filter parameters (manufacturer, type, number, lamels, measures etc.) are to be registered.

AVAILABLE (in blue) and other AIR FILTERS' DATA - PRIZES in HUF (updated: 13th April, 2016.):
NORMAL PANEL AIR FILTERS:

NAME	NUMBER	PRIZE
BMW „factory original"	13721715881	7846.- HUF + 27% VAT
Mann	C26110/1	5565.- HUF + 27% VAT
Bosch	1457429964	3260.- HUF + 27% VAT
Mahle Knecht	LX105	3631.- HUF + 27% VAT
Racer	R3152	2135.- HUF + 27% VAT
Tecneco FM	AR334PM	1988.- HUF + 27% VAT
Unix	P161 H13-02-2564	1186.- HUF + 27% VAT

SPORTS AIR FILTER:

NAME	NUMBER	PRIZE
K&N	33-2059	19678.- HUF + 27% VAT
K&N Cleaning Kit(spray)	99-5000EU	3894.- HUF + 27% VAT

Other filters available elsewhere, but <u>not for the present lab session</u>:
Other NORMAL PANEL AIR FILTERS:

NAME	NUMBER	PRIZE
Champion	U527	1932.- HUF + 27% VAT
SOFIMA	S 1420-A	1813.- HUF + 27% VAT
VALEO	585140	2224.- HUF + 27% VAT
Muller	PA334	1730.- HUF + 27% VAT

Other SPORTS AIR FILTER:

NAME	NUMBER	PRIZE
BMC	FB117/01	18599.- HUF + 27% VAT

Geometry data of the air filter's lamels: *

|	Name	Nr.	Length	Width	Height	Nr of lamel pairs
	Név	*Cikkszám*	a [mm]	b [mm]	h [mm]	n_{lam} [db]
1	Mann Filter	C26110/1	245	137	48	86
2	Bosch	1457429964	243	137	47	75
3	Mahle Knecht	LX105	240	137	47	75
4	Racer	R3152	243	138	48	88
5	Tecneco	AR334PM	240	137	48	92
6	Unix	P161 H13-02-2564	240	137	46	74
7	K&N	33-2059	118	232	19,4	19

*NOTE! The geometry data given in the table above are to be measured! Tables may contain false data!

A_F: The total filter surface /$A_F = 2 \cdot n \cdot (h \times b)$/ of the normal panel air filter can be approximated by using rectangular /($h \times b$)/ lamels, while the sports air filter total filter surface A_F can be approximated by using a combination of rectangular + half-cylindric surfaces. (see image below)
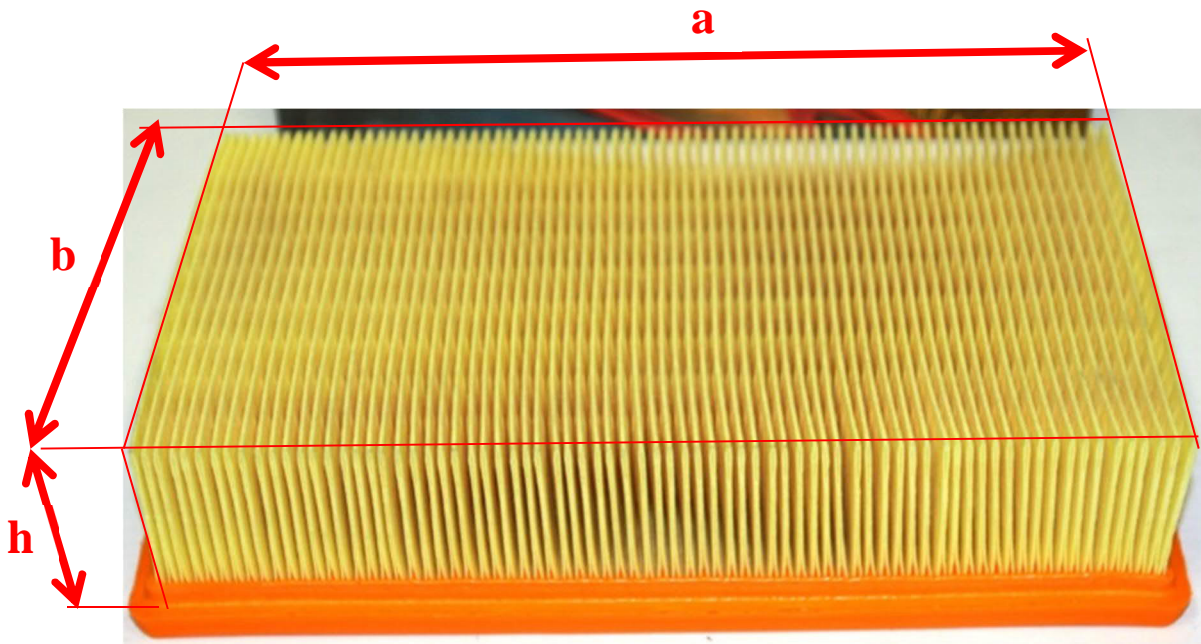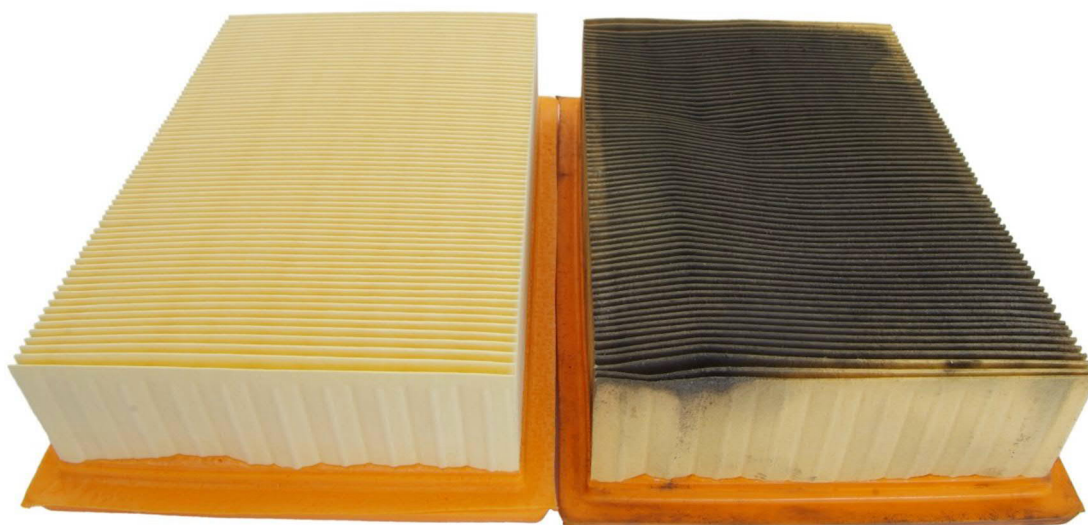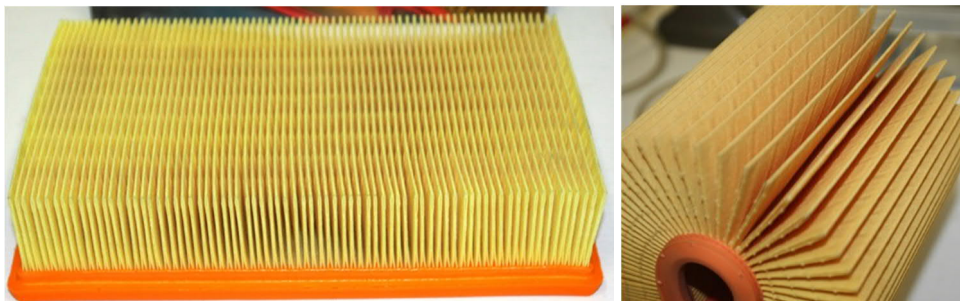

A_{REF}: The projected free surface of the filter can be calculated using $A_{REF} = A \times B$, where A[m] and B[m] length and width are to be measured between the perforated edges, approximately it is also a rectangular shaped projected surface. (see image below)
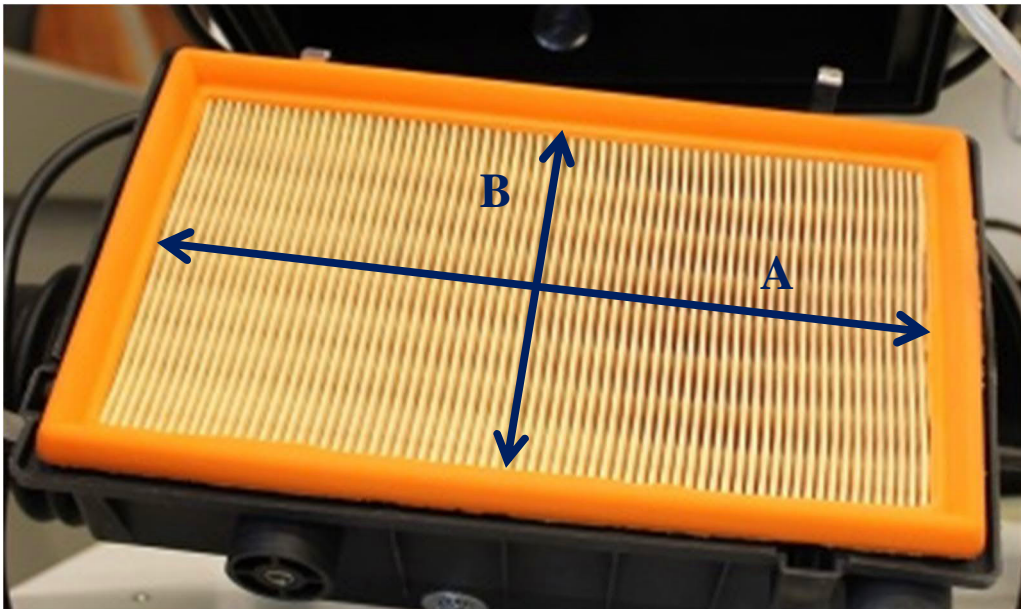
NORMAL („PANEL") PAPER AIR FILTERS:
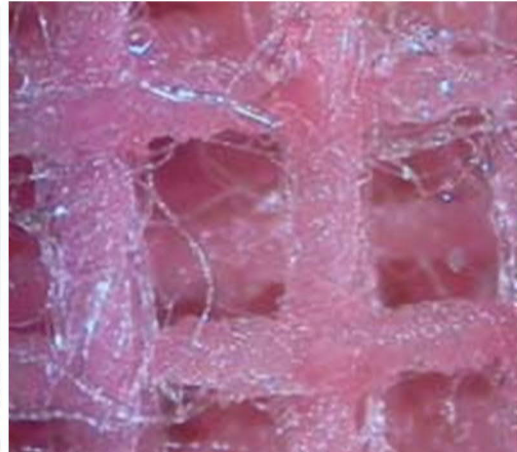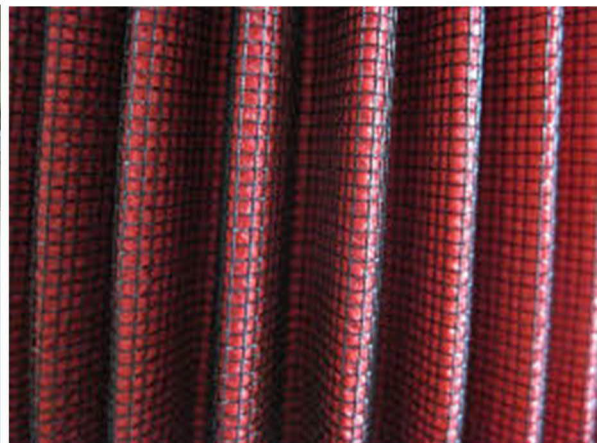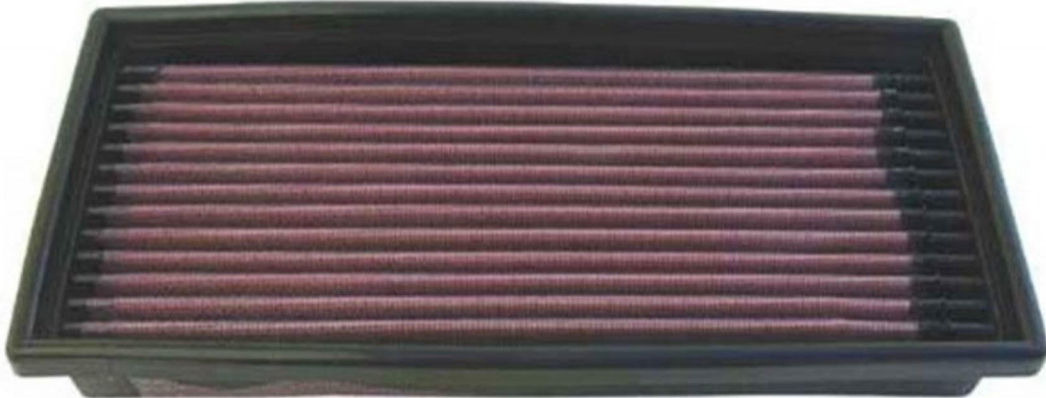
Available filters of various manufacturers:
„BOSCH"; „MANN"; „MAHLE-KNECHT"; „UNIX"; „TECNECO"; „RACER"

SPORTS AIR FILTERS:

Available filters of various manufacturers:
„K&N" sports air filter

Digital manometer: „EMB-001" type digital manometer is used for measuring the filter differential pressure (pressure loss). Connector lines of 4 upstream (red-signed) and 4 downstream (blue-signed) pressure taps are linked to the digital manometer.
(Please register the name, type, serial number etc. of the used digital manometer!)
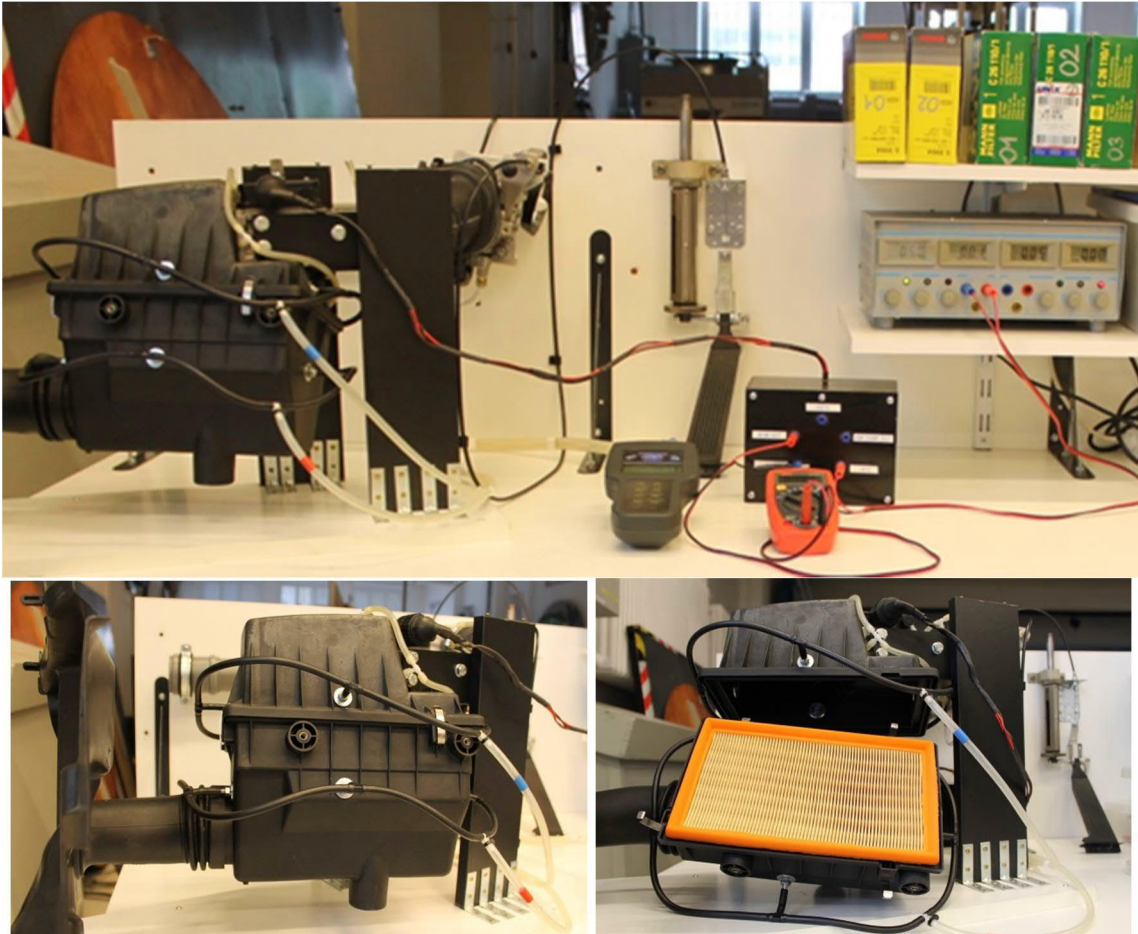
Laboratory power supply: constant supply voltage of 5.0V is connected to the AFM.
(Please register the name, type, serial number etc. of the used power supply!)

Multimeter: output voltage signal of the AFM 0.000-5.000V is measured by the multimeter:
Please register of the whole digit (2 or 3 digits) voltage signal!
(Please register the name, type, serial number etc. of the used multimeter!)

Ambient data: ambient pressure p_0 and temperature $t_0(T_0)$ is to be read on the laboratory PC screen. Air's density is to be calculated using ideal gas law. (R=287J/(kgK)

<div align="center">EVALUATION DIAGRAMS FOR THE LABORATORY REPORT</div>

Compare and evaluate the results of the measured air filters using the diagrams below!
Not all diagrams must be evaluated, but only the ones that were selected by the teacher.
Try to answer the question: „*Which filter to use?*" !

PRESSURE LOSS CHARACTERISTIC CURVES

1) Filter pressure loss vs. flow rate $\Delta p'_F = f(q_V)$
   $\Delta p'_F$ [Pa]; q_V [m^3/s]
2) Filter pressure loss vs. filtration velocity $\Delta p_F = f(v_F)$
   where $v_F = q_V/A_F$, and where A_F is the total cross-section of the filter lamells
   Δp_F [Pa]; v_F [m/s]; A_F [m^2]

LOSS COEFFICIENT CHARACTERISTC CURVES

3) Filter pressure loss coefficient vs. flow rate $\xi_F = f(q_V)$
   where ξ_F [-]; q_V [m^3/s]
4) Filter pressure loss coefficient vs. filtration velocity $\xi_F = f(v_F)$

FORCE ACTING ON THE FILTER MATERIAL CHARACTERISTIC CURVES

5) Force vs. flow rate $F_F = f(q_V)$
   where $F_F = \Delta p'_F \cdot A_{REF}$; F_F [N]
   and where A_{REF} is the reference cross-section of the filter ($A_{REF} = A \times B$)
6) Force vs. filtration velocity $F_F = f(v_F)$

POWER LOSS CHARACTERISTIC CURVES

7) Power loss vs. flow rate $P_{loss,F} = f(q_V)$
   where power loss: P_F [W] = $\Delta p'_F \cdot q_V$
8) Power loss vs. filtration velocity $P_{loss,F} = f(v_F)$
9) Power loss vs. engine speed $P_{loss,F} = f(n)$

RELATIVE POWER LOSS CHARACTERISTIC CURVES

10) Relative power loss vs. flow rate $P_{rel}[\%] = f(q_V)$
11) Relative power loss vs. flow velocity $P_{rel}[\%] = f(v_F)$
12) Relative power loss vs. engine speed $P_{rel}[\%] = f(n)$

MOREOVER, <u>ONLY FOR MSc LAB SESSIONS</u>: PERMEABILITY (α) AND INERTIAL RESISTANCE FACTOR (C_2) FOR CFD SIMULATION of FILTER as POROUS ZONE

Based on the measured $\Delta p_F = f(v_F)$ characteristic curves the following parameters are to be also calculated. The e.g. ANSYS Fluent CFD (Computational Fluid Dynamics) software uses the following expression for pressure drop when air is flown through the filter modelled as a porous zone (layer or volume).

$$\Delta p = -\left(\frac{\mu}{\alpha} v_f + C_2 \frac{1}{2}\rho v_f{}^2\right)\Delta m$$

In the expression Δp is the pressure loss of the filter (the measured Δp_F). The $\Delta p/\Delta m$ [Pa/m] pressure gradient characterises the pressure loss of the fluid flow through the filter material having thickness of Δm. For the thickness of all filter's material using of Δm=1mm is a good approximation. There is a negative sign in the expression since the pressure is decreasing in streamwise flow direction. The fluid's (air's) dynamic viscosity (μ) and density (ρ) is to be calculated based on the measured ambient data (p_0, T_0). In the expression α is the ***permeability*** and C_2 is the ***inertial resistance factor***. These quantities are to be calculated based on measured data points. The expression can be rewritten in the form of $\Delta p = A \cdot v_F + B \cdot v_F{}^2$, where v_F is the filtration velocity. Plot also the results for α permeability and C_2 inertial resistance factor in function of filtration velocity:

13) Permeability vs. filtration velocity $\alpha = f(v_F)$
14) Inertial resistance factor vs. flow rate $C_2 = f(v_F)$

FURTHER GUIDELINES FOR THE LABORTORY REPORT:

Lab report must contain all registered measured data in table format, with units (S.I. or engineering units):
- AFM's plate angular position   (α[°])
- AFM's output voltage signal   ($U_{AFM,out}$ [V])
- differential pressure   ($\Delta p'_F$ [Pa])
- accelerator bowden cable setting   (l [mm])
- filter data (type, manufacturer, number, main dimensions: A, B; lamel dimensions: a,b,h,n)

All measured and calculated data are to be identified clearly in the lab report. All diagrams, comparison graphs must contain title, vertical and horizontal axes with the plotted data name, denotation, with units, and also nomenclature. Textual evaluation of the common plots for all filters is a must.

UNCERTAINTY ANALYSIS

To perform uncertainty analysis on the measurement results and on all calculated quantities is a must. Absolute uncertainties (δX_i) of the given quantities (X_i) are listed below:

(Instructions of the teacher may differ from the listed!)

$X_1 = \Delta p'_F,$	digital manometer, measured differential pressure	$\delta \Delta p'_F$	$= \pm 2$ *Pa*
$X_2 = U_{AFM,out}$	multimeter, measured voltage signal	$\delta U_{AFM,out}$	$= \pm 0{,}001$ V
$X_3 = p_0$	ambient pressure	δp_0	$= \pm 100$ Pa
$X_4 = T_0$	ambient temperature	δT_0	$= \pm 0{,}1$ K
$X_5 = \alpha$	AFM's plate angular position	$\delta \alpha$	$= \pm 0{,}5°$
$X_6 = l$	accelerator bowden cable setting	δl	$= \pm 0{,}5$ mm

Results (absolute, relative (%) uncertainty values) of the uncertainty analysis are to be indicated also in tables of the registered quantities for each data points and also on the diagrams when plotting results of the characteristic curves for the selected filters.

References
- Introduction to Fluid Dynamics (BSc/MSc level) course handbooks: hydraulic losses, porosity modelling.
- Websites of the air filter manufacturers, BMW car parts' and OEM parts' distributors' websites. Let me google for you!
- ANSYS Fluent User's Manual (CFD modelling of flow through porous media, Darcy law etc.)