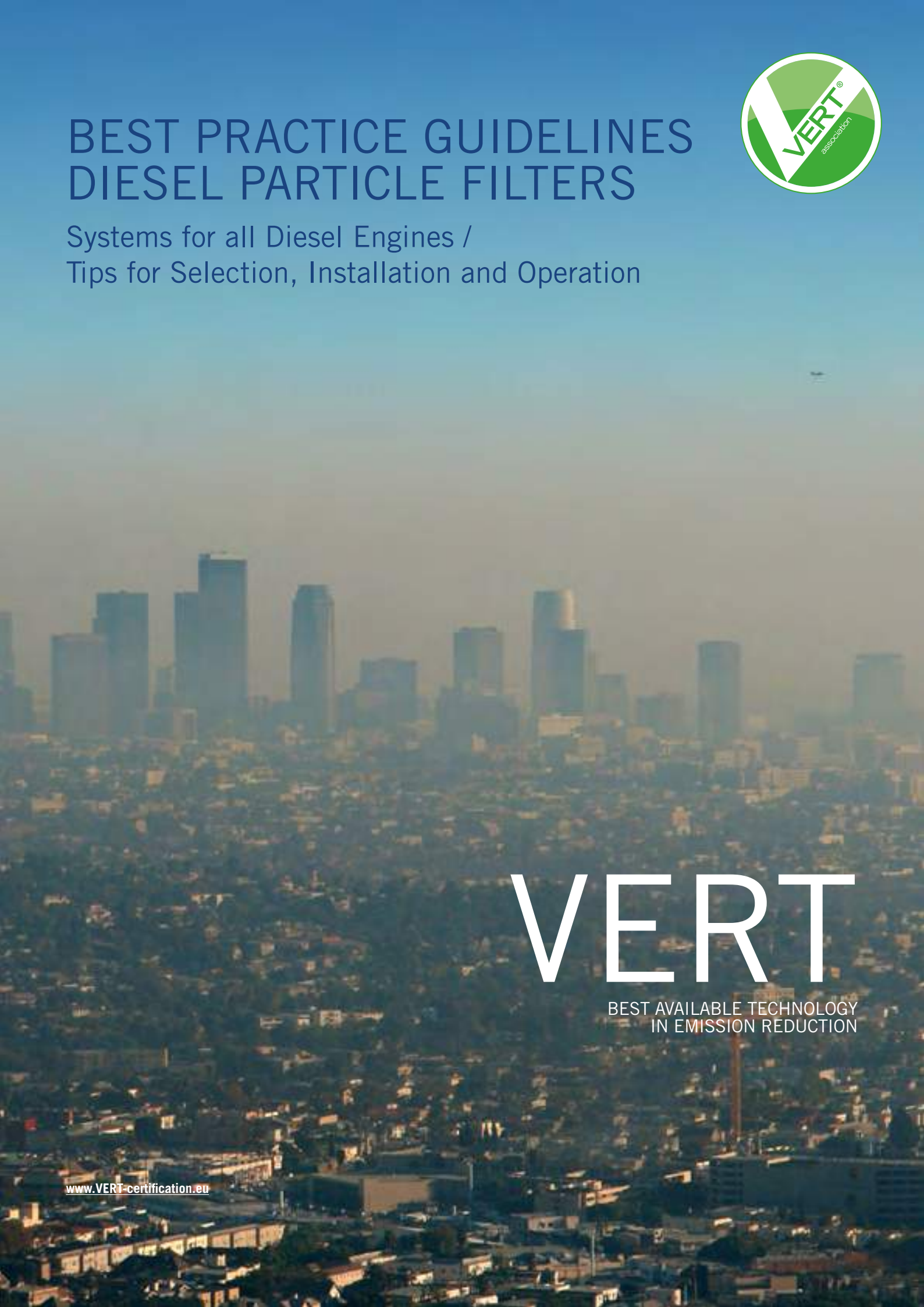
BEST PRACTICE GUIDELINES DIESEL PARTICLE FILTERS

Systems for all Diesel Engines / Tips for Selection, Installation and Operation



VERT

BEST AVAILABLE TECHNOLOGY
IN EMISSION REDUCTION

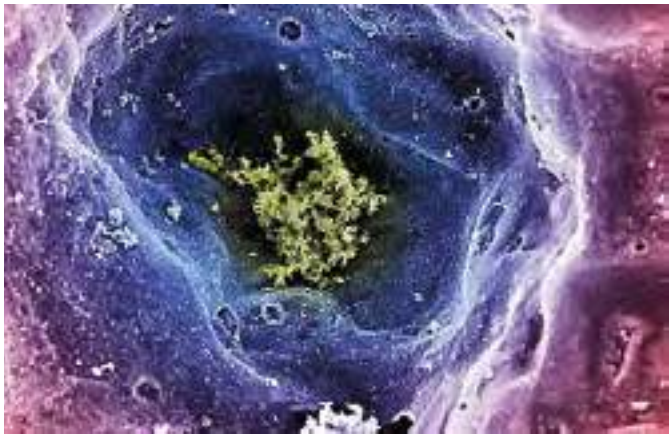
www.VERT-certification.eu

MOTIVATION

Only particle filters can effectively eliminate ultrafine carcinogenic particles from combustion engines.
High efficiency soot-particle filters are available since 1982. Today more than 100 million filters are deployed in road vehicles, construction machines, forklifts, etc. The retrofitting cost is less than a tenth of the avoided health costs.

THE PROBLEM:

Ultrafine particles from combustion engines



Soot particles in human alveoli, deep in the lung
Lennart Nilsson 2004

THE SOLUTION:

Particle filters (DPF) eliminate ultrafine particles

Diesel Particle filter DPF insulated in a steel case, with upstream DOC and control sensors; PEUGEOT 2000

MORTALITY: More than 10,000 persons die daily because of particle emissions from vehicle engines. **Heart attacks kill about 35%, brain strokes kill about 45%, and cancer kills about 15%.** Residents of big cities, children near busy streets, pregnant women and the sick are particularly vulnerable.

PARTICLE SIZE is the crucial parameter. Natural dust particles do not invade the blood circulation since they are too large. But particles from combustion engines are 100 times smaller, about 0.1 µm or 100 nm (for comparison: viruses are in the same size range of 20-300 nm). They easily intrude from the lung into the blood stream and thus enter the brain and the placenta. The particles transport other harmful substances into the organism and remain there, hardly cleaned out or metabolized, persistent toxics.

HEALTH COSTS are about $ 2,000 per kg soot. The OECD estimates 41,000 related deaths annualy in Germany and this costs $ 144 billion, i.e. $ 1,800 per resident. Mortality increases linearly with air pollution. Hence anticipate proportionaly higher costs with larger cities and denser traffic.

CARCINOGENIC POLLUTANTS have no harmless dosage. Since 2012, the WHO classifies Diesel soot as Class 1 carcinogen just like asbestos.

NEW TECHNOLOGIES BECOME only gradually effective, because new standards are only implemented in new vehicles. Fleet renewal occurs after 15-20 years and sometimes longer. DPF retrofitting is therefore imperative and since 1994 successfully implemented in many European cities.

FILTRATION is the only way to remove the highly toxic soot and metal oxide particles (abrasion and lubricant sources) very efficiently from the exhaust gas. **Caution: not all filters are good filters.**

FILTER EFFICIENCY depends not on the engine, but on the pore structure of the filter medium and the correct design. On every engine, a good filter attains filtration rate exceeding 98% for ultrafine solid particles. These particle filters can be applied for all combustion engine applications, Diesel and Gasoline, on-road and non-road and they replace the mufflers.

BAD FILTERS only temporarily store the soot and release it later. Other bad filters only remove the larger particles and pass on the toxic smaller particles. Some bad filters generate additional toxic substances ⟶ only VERT certified filters shall be applied.

FILTER REGENERATION is the self cleaning of the filter through complete conversion of the retained soot into nontoxic gas CO2. Many regeneration techniques are available. The chosen regeneration method depends on how the vehicle is deployed.

FILTER CLEANING is only necessary about once a year to remove ash. That requires dismounting the filter.

FILTERS DO NOT AGE AND DO NOT WEAR OUT. They do require careful mounting and regular testing of engine emissions.

THE MONETIZED HEALTH BENEFITS for society are at least 10 times higher than the retrofit costs. The US EPA estimates the benefit/cost ratio is now 13:1

VEHICLE MATCHING AND FILTER SELECTION

"No Diesel without DPF" is the imperative for ambient air quality.
Each unfiltered vehicle emits more particles than a fleet of 100 vehicles fitted with DPF.

EVERY VEHICLE CAN BE RETROFITTED, BUT

- High raw emissions are a challenge.
- During free acceleration opacity k must be below $1 m^{-1}$.
- Vehicle must be perfectly maintained as per manufacturer's specification especially regarding the intake air filter, oil filter, injection, turbocharger, leak tight exhaust pipe, suspension and noise emission.
- Lubricant consumption must be below 0.5% of fuel consumption.
- Fuel Sulfur content shall be below 10 ppm otherwise sulfur tolerant DPF systems must be deployed.
- Avoid prolonged idling which is wasting energy.
- DPF fitted vehicles must be more carefully diagnosed, because engine problems do not clearly manifest in the exhaust as one is used without DPF (blue smoke, soot etc.)

NO AGE LIMITS for retrofitting, but the retrofitting benefit/cost do diminish with remaining life expectancy. Hence old vehicles should no longer be deployed but rather scrapped.

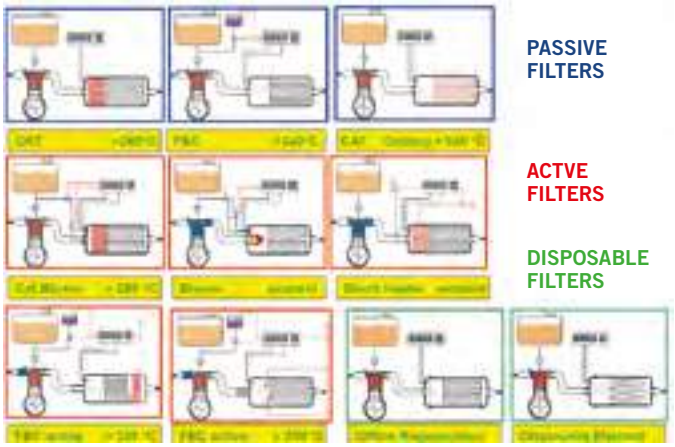
VERT CERTIFICATION REQUIRES

- Filtration > 98% for ultrafine particles
- No toxic secondary emissions permitted
- Back pressure when new is below 50 mbar
- Maximum back pressure below 200 mbar
- Endurance test 2000 hours without deterioration
- Electronic onboard diagnosis OBD integrated
- Design, construction and materials verified

See VERT Filter List www.VERT-certification.eu

VERT FILTER MANUFACTURERS are audited and they guarantee function and operation during 2 years.

A LARGE VARIETY OF FILTER SYSTEMS is necessary because of deployment diversity, e.g. between a city bus, a garbage truck, an excavator, a forklift and a crane.



EXPERIENCE is key. VERT filter manufacturers select the correct filter from their portfolio. All applications have been repeatedly done during the last 20 years. About 8.000 retrofits are documented and accessible in the VERT database:
http://vert-certification.eu/j3/index.php/filters/filter-llist-database

IN VERY SPECIAL CASES FILTER SELECTION

requires analysis of the duty profile, especially the exhaust gas temperature. The filter manufacturer uses an instrumented data logger to determine typical operating conditions during 2-3 weeks.

The results indicate whether the filter can be passively regenerated or whether active regeneration is necessary. Both methods are available and proven in many product families.

Only deploy VERT certified filters. Their function is tested and the manufacturer guarantees quality. A database with applications is accessible at www.VERT-certification.eu

FITTING / TESTING / APPROVAL

FILTER SYSTEMS FULFILL THE FUNCTIONS

Filtration – Regeneration – Electronic monitoring – Noise attenuation

Modular design with variable inlet and outlet cases

Fixation to the vehicle frame must respect the very high vibrations

Parallel substrate arrangement for larger engines

FBC-Filter-System with electric activation of the regeneration

All Filter systems include electronic monitoring (5) and alarms (1); this active system uses FBC (6).

BEFORE RETRO FITTING

- Verify that the engine is maintained and technically in good condition.
- Change to Low SAPS lubrication oil
- Measure exhaust-gas opacity during acceleration

Exhaust opacity k < 1 m^{-1}

- Submit engine and vehicle data (type, mileage, age) exhaust opacity and muffler drawing to the filter vendor.
- inform the filter vendor about the application and driving profile and exhaust temperature; if not known measure exhaust gas temperature during operation.
- Determine the filter regeneration method (filter vendor).
- Determine the filter size (filter vendor)
- Do not exceed the maximum back pressure that the engine manufacturer specified.

FITTING PROCEDURE

- Locate filter as close to engine as possible
- Dismount muffler – is replaced by the particle filter
- Mount filter ensuring isolation to engine vibrations and a shock absorbing suspension.
- Provide access to filter elements for filter cleaning and instrumentation ahead of the filter.
- Insulate the filter for safety. The insulation also keeps the filter warmer and thus promotes regeneration.
- Mount the OBD protected from water splash. Provide access for data extraction.
- Wire the pressure and temperature sensors. Install data antenna for remote fleet control.
- Place alarm display in cockpit.
- Instruct own workshop team.
- Store spare parts and replaceable filter elements.

APPROVAL TEST

- Test functioning filter, electronics and display.
- Verify filtration with a particle counter.
- Verify backpressure
- Verify noise attenuation
- The filter manufacturer and vehicle/engine owner sign the approval report.

Contents:

Addresses of operator and filter manufacturer;
Vehicle, engine and filter data;
Back pressure at maximum RPM;
Opacity before and after filter retrofit.
Optional: noise level before and after filter retrofit;
Optional: function check
OBD and alarm display;
Signature of filter retrofitter and operator.

This test /approval has a contractual character between buyer and seller and for the authorities. The test results must be recorded in an approval report with two signatures and dated. It is a **guarantee document.**

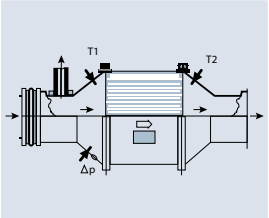
SAFETY ASPECTS

- Driver's view must not be obstructed.
- No excessive ambient and surface temperatures.
  ⟶ if necessary, heat shielding and filter insulation.
- Vehicle's ground clearance guaranteed.
- Apply spark arrestor for interior and forest operation
- Comply with mounting and fixing specifications. (Particle filters are heavier than the replaced muffler)

TRAINING Retrofitting the particle filter includes the backpressure display module in the driver cabin. The drivers/operators must be thoroughly and effectively instructed. He must react appropriately to the alarm display (flashing or continuously illuminated). The filter manufacturer or the retrofitter will help with training. The successful training must be documented.

OPERATION AND MAINTENANCE

The following recommendations are valid for all Diesel vehicles with exhaust gas after-treatment systems irrespective whether original equipment or retrofitted.



P and T sensors and access for measurements upstream

Electronic monitor (OBD) and alarm panel are standard, GSM is optional

Temperature and pressure measurement

Data download or GSM fleet control

Label indicates maintenance deadline

GENERAL

To ensure emission stability, regular inspection and maintenance of filter and engine are mandatory. The electronic monitoring provides supporting information. Maintenance must be documented. A sticker indicates when the next maintenance is due. Organized preventive maintenance reduces costs.

PERIODIC VERIFICATION

Verify at strict intervals: leak tightness of the exhaust gas pipes, suspension of the filter system, electrical connections and continuity of the pressure measurement line. Material discoloration is an overheating symptom. Soot in the tail pipe indicates inadequate filtration.

DIAGNOSIS DATA

The electronic function monitoring OBD provides temporal data of exhaust gas temperature and exhaust gas backpressure. Any excesses trigger the OBD alarm. The evaluation of the logged data enables detailed assessment of the filter system and facilitates important decisions on corrective action.

EMISSION TEST

During maintenance, the particle emission must be measured at low idling using a certified PN instrument. If PN is > 100'000 1/cc, then a second measurement upstream of the filter is done to determine the filtration efficiency. The cause of low efficiency might be filter damage. It can be repaired if less than 10% of the filter surface is damaged. Else the filter must be replaced. When the PN count upstream of the filter is excessive then the problem is in the engine that must be scrutinized and rectified.

REGENERATION ADDITIVE

Some DPF systems operate with fuel additives (FBC). Only VERT certified additives shall be used. Demand proof and guarantees from the additives vendors to ensure that these additives do not negatively affect the engine. Do not use additives without filter.

IMPACT ON THE ENGINE

The filter system only influences the engine through the backpressure, which is slightly higher than the backpressure of the muffler that it replaces. The fuel consumption can increases by 2-3%. This does not impact the engine and its operation unless the backpressure exceeds the 200 mbar limit for long time. The OBD ensures compliance.

ALARMS

Warning lamps and acoustic alarms must be strictly observed. Ignoring alarms can result in dangerous overheating of the system. The OBD surveillance system records all ignored alarms, in its inerasable error log, and inaction consequently implies guarantee invalidation.

FUEL AND LUBRICANTS

Normally fuel sulfur content should be less than 10 ppm. For higher sulfur content special sulfur tolerant filter systems must be applied. Both Diesel fuel and lubricants have incombustible contents that result in ash. This ash, together with metallic engine abrade, deposit in the filter. Hence only use low ash forming lubricants (so-called Low-SAPS oils).

FILTER CLEANING

Consequently the filer must be periodically cleaned when exceeding backpressure of 200 mbar despite satisfactory regeneration outcome. The usual interval is about 1,000 operating hours; maybe much longer when a low-ash engine lubricant is used. Metal filters can be manually cleaned with a high pressure cleaner. Ceramic filters shall not be cleaned with hot water or steam. A special filter cleaning machine must be used. The figure shows a filter cleaning system from the company PURITECH. After inspection, the filter element is heated in an oven to 650°C to burn off the soot. Subsequently the ash is blown out with a pulsating air jet. The cleaning attains more than 95 % and can be repeated 5-6

times. The ash is toxic waste and must be disposed according to local rules. To protect occupational health, filter cleaning must be done in a hermetically closed machine.

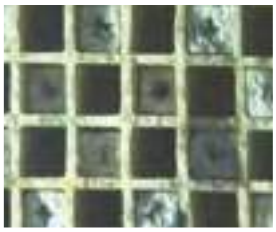
FAULTS – REASONS AND ACTIONS

Most failures and damages have these causes:
Alarms ignored, poor maintenance of filter systems and the engine, unsuitable fuel or lubricant.

Dilatation, vibration isolation and shock absorbers missing
→ Cracks inevitable

Deposits at inlet surface
→ Air intake filter damage?
Sulfate formation?

Vibration damage from oscillation across the bellows.

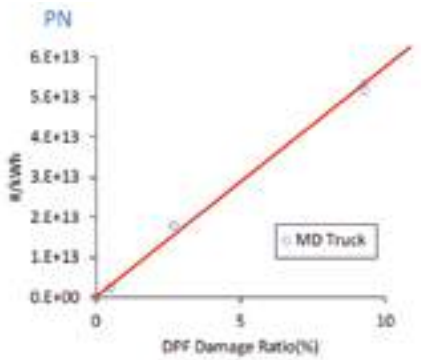


Ash deposition far too high, maintenance problems
→ Replace

Filter perfect
→ End pipe is clean

FILTER CLOGGING is due to inadequate regeneration. An emergency remedy is to spray the filter with a VERT certified fluid that loosens the deposited soot. Else substitute the filter and clean it externally, like ash cleaning. Excessive deposits are probably due to changed vehicle operation at low exhaust gas temperatures. That can only be exceptionally tolerated. The regeneration method must be revised. Frequent causes of filter clogging are by increased soot formation due to deteriorating engine combustion (injection, turbocharging), intake air filter pollution, higher lubricating oil consumption, or a faulty (oil leaking) turbocharger.

FILTER RUPTURE symptoms are visible soot traces in the tail pipe. The outflow surface of the filter element reveals type and extent of the damage. It could be a small thermal crack. The cause could be thermo-shock due to overloading, or perhaps the alarm was ignored. Minor filter damage can be repaired by plugging the damaged cells with a special ceramic mass.



The degree of damage can be detected by PN-measurement

Source: Yamada, ETH-NPC 2015

Small internal cracks are clearly visible by single black cells on the filter exit side

MALFUNCTION OF THE OBD MONITORING: This fault is serious and must be immediately rectified to ensure safety and guarantee validity. Do the following: Evaluate the error codes. Inspect pipes, cable connections and sensors. Assess the logged data.

HIGHER FUEL CONSUMPTION AND NOTICEABLE POWER LOSS are usually engine related problems and not in the filter. The filter's impact on fuel consumption and power delivery are only consequent to the back-pressure. The penalty is only 2-3 % at maximum backpressure of 200 mbar. Unless the backpressure stays far above this value and alarms are ignored the engine must be diagnosed first. Excessive backpressures periods higher than 500 mbar can overheat the engine, reduce power and make it difficult to start the engine, even disconnect the exhaust tube elements.

ALARMING NOISE Either leakage or vibration. Both are serious faults which tend to aggravate the damage soon. Must be immediately diagnosed and rectified to ensure safety of the vehicle and the driver or passengers who might suffer from higher air pollutants in the cabin since bus floors are usually not tight.

ALARMING SMELL

Either leakage of overheating. Both are serious faults which tend to aggravate the damage soon. Must be immediately diagnosed and rectified to ensure safety. If leakage it can be oil leakage, fuel leakage, gas leakage or additive leakage – all these liquids are inflammable. Overheated material underneath the vehicle like plastic hoses must be avoided ⟶ improve insulation or heatshield.

WHITE SMOKE

Is usually just water vapour from condensation or rain water the filter was soaked during standstill over night. Avoid vertical endpipes or close them with a lightweight selfopening flap.

SAFETY RULES AND TROUBLE SHOOTING

See VERT Filter List and trouble shooting:
www.VERT-certification.eu

CONTROL INSTRUMENTS AND DIAGNOSIS

Emission curtailment is only as good as its management.
These include onboard diagnosis, workshop verification and official regulatory inspection.

On Board Control
Manufacturer PNE

Alarm Display
Manufacturer CPK

PN exhaust instrument
Manufacturer TSI

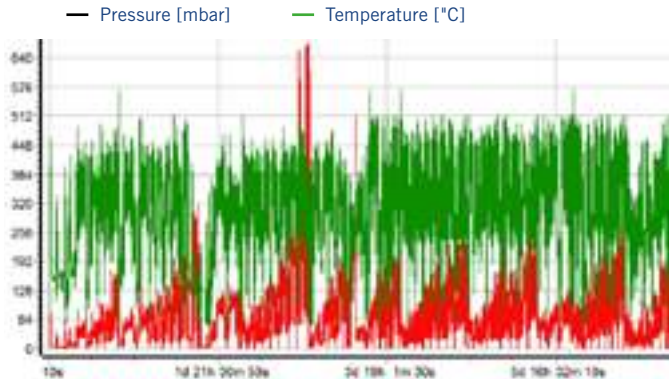
PN exhaust instrument
Manufacturer TESTO

PN ambient instrument
Manufacturer TESTO

Opacity is obsolete
– too insensitive

ELECTRONIC OBD MONITORING IS MANDATORY

for all VERT certified filters. Data is logged every second for back-pressure and temperature before filter. The logged data must be stored for at least 3 working months. The supplementary error data is not erasable.
The stored data can be locally retrieved or wirelessly transmitted via GMS to a central supervisor station.
The OBD monitors the sensors signals and itself, issues alarms, continuously assesses information on response of filter and the engine, and prepares data based proposals for preventive maintenance.



ALARMS are announced acoustic and optic to the driver or wirelessly transmitted to a central supervisor. Moreover these alarms are stored tamper proof. This enables determining cause of failure in damage claims. The usual alarms are:

- Pre alarm if back-pressure exceeds 150 mbar (amber)
- Main alarm if back-pressure exceeds 200 mbar (red)
- Filter damage if back-pressure decreases rapidly
- Cleaning when back-pressure exceeds 200 mbar

Countermeasures to reduce engine power are permissible when the alarm thresholds are exceeded. However the operator must approve. Bypassing the filter is not permissible.

WORKSHOP MEASUREMENTS

of particle emissions are mandatory as particle number PN [1/cc] when particle filters are deployed. For onsite and field measurements, instruments were developed that comply with the following guidelines:

- The Swiss VAMV Guideline 2000 specifies instrumentation for the measurements of gaseous emissions
- The Swiss VAMV Guideline 2012 specifies instrumentation for the particle concentration PN
  http://www.admin.ch/ch/d/as/2012/5371.pdf

Instruments are either the condensation counter CNC from manufacturer TSI, or the electrical diffusion charging of nanoparticles from manufacturers TESTO and others. These instruments are available and proven. These enable accurate filtration rate measurements, even in low idling, so precisely that 1% filtration deterioration is detectable and therefore filters are reparable at low cost. For the measurement of gaseous emissions, many field instruments are available from TESTO, AVL, MAHA and other manufacturers. These are based on electro-chemical cells or infrared sensors. The measurements are very important to diagnose engine deterioration.

ENGINE DIAGNOSIS

is more difficult when a filter is fitted since the filter is “masking” the engine. Engine smoke and smells are trapped in the filter and no longer perceptible indications of impending engine failure. Hence exhaust gas measurements are necessary to detect engine problems early and initiate cost reducing preventive maintenance.

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GLOSSARY
CNC: Condensation nucleus counter
Diffusion charging: electrical charging of particles prior to counting
DOC: Diesel Oxidation Catalyst
DPF: Diesel Particle Filter
GMS: Wireless data transmission
Low SAPS: Lubricant low in Sulfur S, Phosphor P and Sulfate Ash
mbar: 1/1000 bar
Nanometer nm: 10^{-9} m; one millionth of a mm
Nanoparticles: lung invasive particles < 1000 nm
OBD: On board diagnosis = electronic monitoring
OECD: Organization for Economic Cooperation and Development
Opacity: Exhaust gas opacity unit k [1/m]
PM: Particle Mass per kWh
PN: Particle Number per Cubic centimeter
ppm: parts per million
Secondary emissions: can occur in DPF, DOC and SCR
VAMV: Swiss Exhaust Guideline
VERT: Verification of Emission Reduction Technology
WHO: World Health Organization

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The VERT Association publishes on its web site information on the topic of particle filter retrofitting. The site also has a comprehensive database of already retrofitted vehicles and machines. The VERT Filter List documents the certified filter systems and their manufacturers. www.VERT-dpf.eu

The PDF version of this publication can be downloaded at www.VERT-certification.eu