Appendix 4: Engine technology and scheme compliance

This appendix provides technical information on the ways in which vehicle operators can make their vehicle compliant with the requirements of the scheme.

A4.1 Eligible Euro I and II engines

The London Low Emission Zone Scheme Order specifies that heavy duty tested vehicles (ie vehicles over 3.5 tonnes) must meet the Euro III standard for particulate matter (PM) for phase 1 of the scheme, which was introduced on 4 February 2008. However, there are some Euro II and a few Euro I heavy duty tested engines that even though the overall emissions of all regulated pollutants are worse than the Euro III standard, the engines may have sufficiently low particulate matter emissions to meet the requirements for phase 1 of the scheme, even without modification.

Some of these engines have been identified because they are eligible for a Reduced Pollution Certificate (RPC) issued by the Vehicle Operating Services Agency (VOSA), part of the Department for Transport (DfT), because of their low particulate matter emissions. Others may not qualify for the RPC scheme because the engine manufacturers have not provided DfT with the emissions evidence needed at the time that the RPC scheme was introduced, but may still met the required scheme emissions standard.

These engines are typically early examples of advanced electronically controlled engines that manufacturers introduced before the Euro III standard made such controls essential. They are able to meet the Euro III standard for particulate matter, but are only certified as meeting Euro II levels for other regulated pollutants. Some are models of engines which have been fitted with particulate traps or oxidative catalysts that reduce the particulate matter emissions sufficiently to meet the RPC requirements.

Transport for London (TfL) has worked with vehicle and engine manufacturers who have provided engine certification data that confirms these engines meet the necessary particulate matter standard for the scheme, and therefore qualify for a Low Emissions Certificate (LEC). These vehicles must be inspected by VOSA to ensure they have the specific engine which has been shown to meet the required particulate matter emissions standard. They must also undertake an annual inspection and smoke test to maintain this certificate. This is the same inspection and test regime that vehicles fitted with an abatement device take. While it is not possible to measure particulate matter emissions in this test it provides a means of checking the engine is still performing as expected and so is working within the emission limits certified when the engine was first manufactured.

As these vehicles are unmodified, this route provides a low cost route for owners of these vehicles to meet the emissions requirements of the scheme until 2012, when these vehicles no longer satisfy the emission requirements without modification. This is because there is a large difference between Euro III and Euro IV emission limits. The scheme order also explicitly excludes Euro 2 light duty tested vehicles to qualify without modification.

A4.2 Overview of abatement technology

The mass and size of diesel particulate matter have been receiving increased attention due to adverse health effects from the smallest ('fine' and 'ultrafine') particulates. One method of reducing the mass of PM and numbers of fine particles is to employ diesel particulate abatement or exhaust 'after-treatment' technology. This is now well established, based either on oxidation catalysis and/or diesel particulate filter (DPF). Over 100,000 HGVs and buses have been fitted with these devices across Europe, including approximately 20,000 to 30,000 in the UK.

Such abatement devices can achieve significant levels of PM emission reduction, ranging from 25-30 percent for an oxidation catalyst, 50-60 percent for a partial filter to over 95 percent for a full-flow filter. This performance is based on the **mass** of particulate collected on a filter paper during an approved emissions test according to existing standards. While there is no single methodology for determining the number of fine (or ultrafine) particles, much international research has been undertaken and proposals for a standard particulate number/size metric are emerging for future vehicle and engine certification.

The range of scheme certified PM abatement equipment that can be retrofitted to a heavy duty diesel vehicle is presented in Table A4.1. This table also shows how the equipment improves a vehicle's base Euro standard for PM.

These suppliers have been certified via TfL's Low Emission Certificate accreditation scheme, based on either physical testing or a review of third party accreditation, plus a supplier assessment. These activities are undertaken on behalf of TfL by one of two recognised certification bodies – the Energy Saving Trust (EST) and the Vehicle Certification Agency (VCA).

Those PM abatement devices which employ catalysis are usually highly effective in reducing carbon monoxide (CO) and hydrocarbons (HC), as well as PM. Abatement devices do not directly control oxides of nitrogen (NO_X), with any small NO_X emission reduction usually attributed to 'internal exhaust gas recirculation or EGR' caused by increased exhaust back pressure.

Table A4.1 List of equipment manufacturers and technology type for heavy duty vehicles.

	Base vehicle Euro PM standard			
	Pre-Euro	Euro I	Euro II	Euro III
Abatement supplier **Technology type: 'trade name'**	**Resulting Euro PM standard**			
Astra Vehicle Technologies DPF with FBC – active regeneration: 'Adastra DPF'	Euro III	Euro III or Euro IV	Euro IV	Euro IV
Cawdell Group C-DPF: 'Purifilter'	Euro III	Euro III or Euro IV	Euro IV	Euro IV
Cawdell Group DPF with offline regeneration: 'Combifilter'	Euro III	Euro III or Euro IV	Euro IV	Euro IV
Clean Diesel Technologies DPF with FBC: 'Purifier e4'	Euro III	Euro IV	Euro IV	Euro IV
Dinex Exhausts C-DPF: 'DiPEX'	Euro III	Euro III or Euro IV	Euro IV	Euro IV
Dinex Exhausts Catalysed partial filter: 'DiDOC+'	-	-	Euro III	-
Eminox C-DPF: 'CRT'	Euro III	Euro III or Euro IV	Euro IV	Euro IV
Eminox DPF with FBC – active regeneration option: 'Eminox FBC'	Euro III	Euro III or Euro IV	Euro IV	Euro IV
GAT Eurocat C-DPF: 'HD Eurofilter'	Euro III or Euro IV	Euro III or Euro IV	Euro IV	Euro IV
GAT Eurocat Catalysed partial filter: 'Multiflow'	-	-	Euro III	-
KleenAir Systems Ltd Catalysed partial filter: 'Free-Flow Filter'	-	-	Euro III	-
Per-Tec Ltd. Electrically-regenerated partial filter: 'PowerTrap'	-	-	Euro III	-
Pirelli Ambiente DPF with FBC: 'Feelpure'	Euro III	Euro IV	Euro IV	Euro IV

A4.3 Scheme eligible PM abatement technology categorisation

The following sections describe those PM abatement technologies which have been accredited via TfL's LEC certification scheme as enabling non-compliant vehicles to meet the LEZ emission standards; partial filters, full-flow (or wall-flow) DPF – either passive or active.

A4.4 Partial filtration or particulate separation

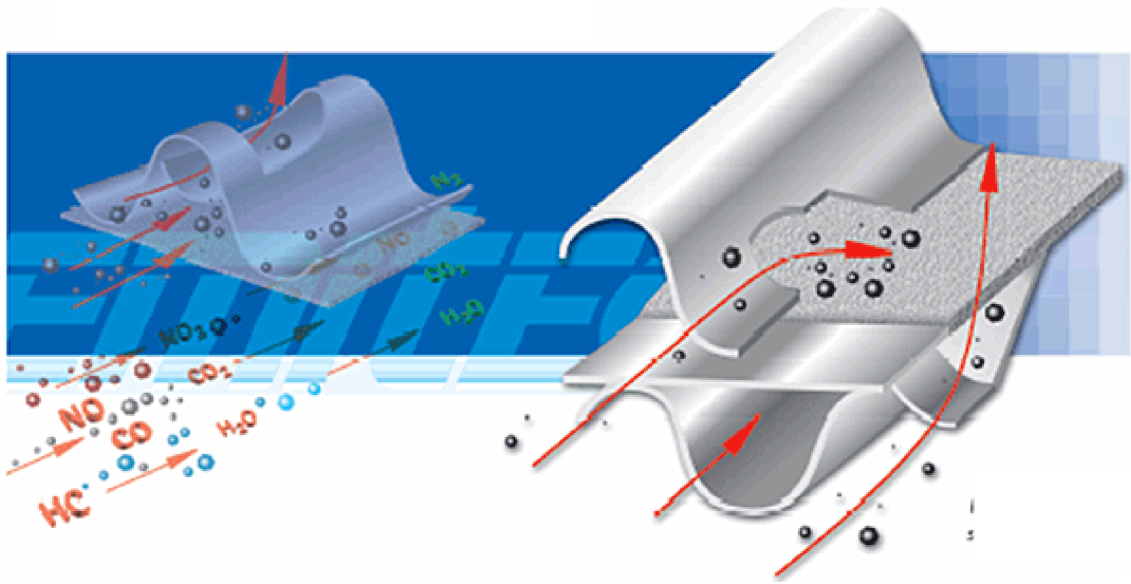
Partial Filter

Several European truck manufacturers meet the Euro IV (and Euro V) PM emission limit (of 0.02 g/kW.hr over the steady state ESC test; 0.03 g/kW.hr over the transient ETC cycle) without the need for full- (or wall-) flow particulate filtration. One of the most prominent users of partial filter technology is the German MAN Nutzfahrzeuge

Group, who uses the PM-KAT® filter, supplied by Emitec. The particulate separator system has an open, non-blocking channel structure, which is clog- and maintenance-free and requires no extra operating agent. The MAN PM-KAT is claimed to achieve approximately 50 percent reduction in the overall particulate mass as well as a 60-90 percent reduction in the number of nanoparticles (10-100nm range).

The PM-KAT filter particulate separation is effected by the formation of turbulence during the deflection of exhaust gases in the separator and their passage through a sintered metal fabric or fleece. The reduction of particulates retained in the fabric is the result of a chemical reaction brought about with the aid of nitrogen dioxide (NO_2) formed in the oxidising catalytic converter. An image of the structure is shown in Figure A4.1.

Figure A4.1 Image of MAN PM-KAT ® filter system.



In contrast to full- or wall-flow filtration, the MAN system operates with both a through-wall (or rather, through-sintered metal mat rather than ceramic) and bypass flow principle. This avoids ‘plugging’ of the filter with particulate matter in the event of insufficient regeneration temperatures. The particle separator diverts the exhaust gas flow into adjacent channels and those retained in the sintered metal fabric mat are stored temporarily and then burnt (oxidised) at approximately 200°C using NO_2.

The Emitec technology is not currently LEC accredited, although similar partial filter technologies are. What these have in common is that they use the principles of turbulence and aerodynamic effects to cause particles to be directed to deposit and/or agglomerate in or on a metallic material which is normally catalysed (ie coated with a precious metal washcoat), to promote regeneration.

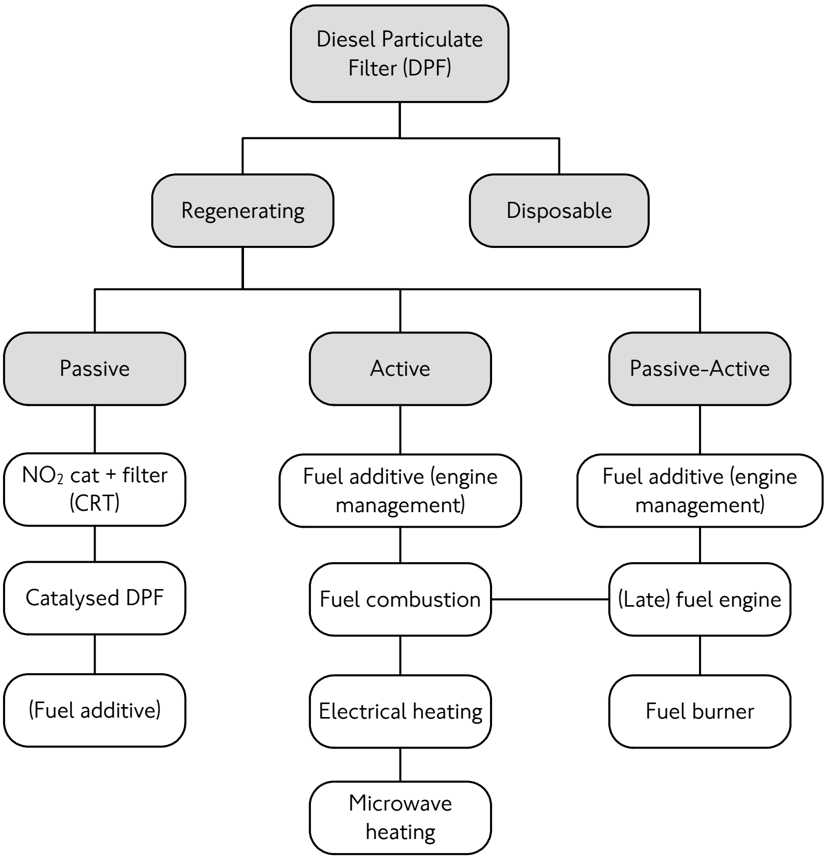
Low Emission Certificate accredited partial filter systems:

- KleenAir Systems – Free-Flow Filter
- GAT – Multiflow
- Dinex – DiDOC

A4.5 Full-flow (or wall-flow) filter – Diesel Particulate Filter

Classification of a full-flow Diesel Particulate Filter (DPF) can be made by the regeneration method, as outlined in Figure A4.2. Disposable-type filters (which collect particulate and when 'full' are removed and disposed of) are not a practical or cost-effective solution for road vehicles. The remaining DPFs can be further classified by their regeneration method, which can be passive, active or a combination of both techniques, as seen in Figure A4.2.

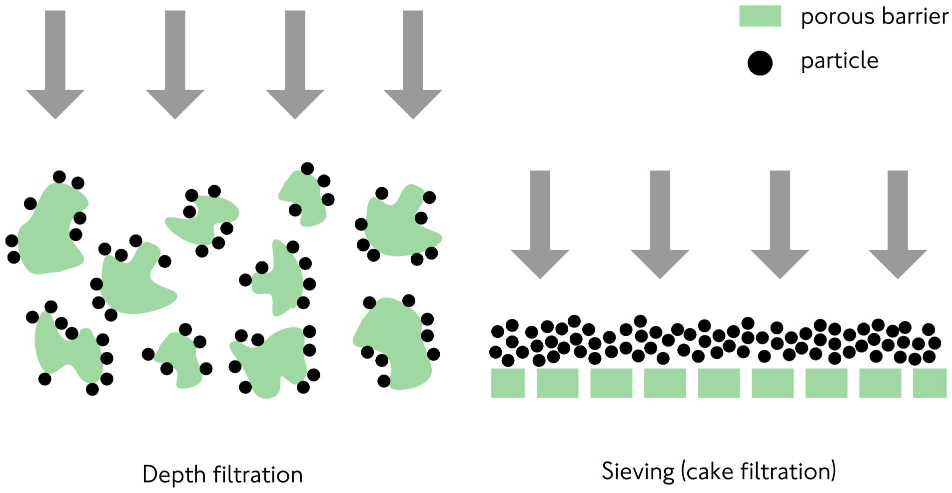
Figure A4.2 Diesel particulate filter classification by regeneration method.



DPFs are characterised by their construction which forces exhaust gas through the structure of the filter. So-called 'wall-flow' construction has quickly become the most popular diesel filter design. They are derived from flow-through catalyst supports where channel ends are alternately closed to force the gas flow through porous walls which act as filters. Another, more thermally robust substrate material is sintered metal (known as the Sintered Metal Filter, or SMF). Filters are usually available in cylindrical form, suitable for 'canning' or packaging into a stainless steel vehicle exhaust or muffler system.

The filtration mechanism in ceramic monoliths is usually a combination of depth and sieving filtration. Initially, diesel particulates are separated from the exhaust gas stream and retained in the pores within the walls. The material porosity may be 45-50 percent or higher, and governs the overall filtration efficiency. With increasing filter load, a layer of particulate may build up at the surface of the inlet channels. After that layer develops, it acts as a filtration cake itself and actually improves filtration efficiency. These two types of filtration are shown in Figure A4.3.

Figure A4.3 Types of diesel particulate filtration.



Wall-flow monoliths have high filtration efficiencies, often more than 90 percent of PM mass. Reduction of the smallest particulates – 'nanoparticles' can be as high as 99.9 percent by number. Drawbacks of monolith filters include the fact that relatively high pressure drop and fast pressure drop both increase with increasing particulate loading, which may lead to a complete clogging or 'plugging'. For filter durability, the regeneration process of wall-flow monoliths has to be designed as to eliminate high temperature peaks due to exothermic (gives off heat) particulate combustion or regeneration. Ceramic monoliths may suffer premature thermal damage (such as melting or cracking) in filter systems which are not designed and specified for a given application.

A4.6 Passive: Catalysed Diesel Particulate Filter / Continuously Regenerating Traps

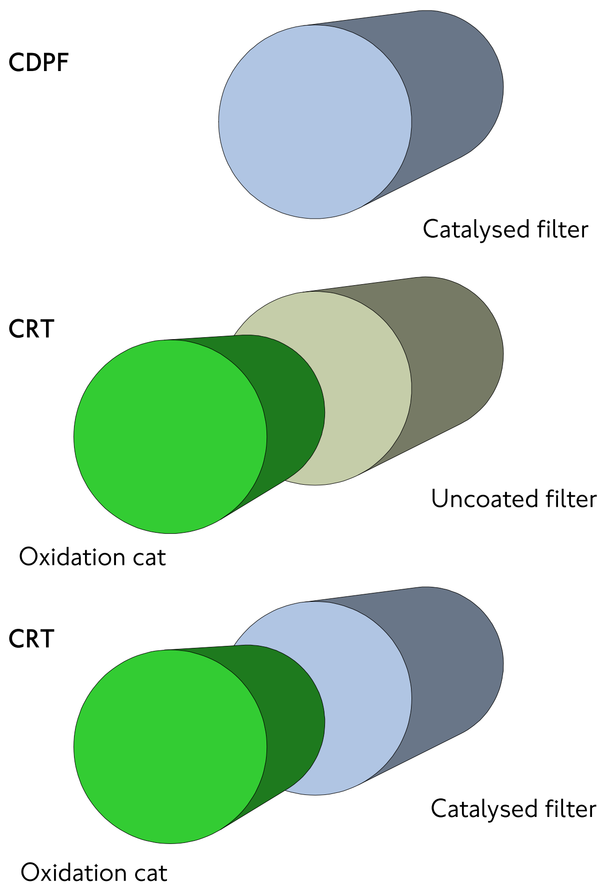
The most common types of DPF used in the UK are those that convert NO to NO_2 in the exhaust stream and use the NO_2 to continuously oxidise the particulates that are held in the filter. In these systems, the regeneration of the particulate matter will happen automatically providing the right conditions exist for oxidation – a combination of both sufficient oxidants and adequate exhaust gas temperatures being available in the exhaust stream. Particulate generally requires temperatures in excess of 550-600°C to burn in air, whereas with the Continuously Regenerating Traps (CRT) or Catalysed Diesel Particulate Filter (CDPF) systems the regeneration temperatures can be reduced to 250°C or below. If the exhaust gas temperature is below this threshold for long periods (eg during long periods of idling or low engine loads), the particulate continues to accumulate which will cause the backpressure to increase and the filter will be at risk of an 'exotherm' (a run-away regeneration generating excessive heat which can crack or melt the ceramic monolith).

It is well known that NO_2 is more active in oxidising diesel particulate than oxygen. The NO oxidation can occur either in a stand-alone oxidation catalyst upstream of the uncoated filter or in the filter monolith itself which is impregnated with a precious catalytic metal – normally platinum. Johnson Matthey has developed a DPF which employs an oxidation catalyst and CDPF (known as Catalysed CRT) to further enhance the system's performance. These configurations are demonstrated in Figure A4.4.

The efficiency of the CRT or CDPF in reducing PM emissions is typically 85-95 percent (by mass and up to 99.9 percent by number), dependent on the use of ultra low sulphur fuel. At high exhaust temperatures, the CRT or CDPF can generate sulphates by catalytic oxidation of sulphur dioxide (SO_2) in the exhaust to sulphur trioxide (SO_3). The gaseous SO_3 can penetrate the porous walls and pass through the filter and later combines with water to form sulphate particulates when cooled down in the emission sampling system (known as 'sulphate make'). When fuels of higher sulphur content are used, catalysed filters may actually increase the total PM. Platinum (Pt) has a strong tendency to form sulphates in diesel filter catalysts and therefore high Pt loading catalysts can only effectively control total PM emissions in conjunction with ultra low sulphur fuel. Fuels even with 350 ppm sulphur, commonly referred to as 'low sulphur fuels', can cause considerable sulphate emission problems.

Large numbers of CRTs and CDPFs have been installed as retro-fit devices worldwide, and many have been fitted and certified in the UK under the RPC scheme. This technology can therefore be considered both reliable and feasible. Some new diesel truck and bus models are now equipped with this type of DPF.

Figure A4.4 Catalytic diesel particulate filter configurations.



Low Emission Certificate accredited passive catalytic DPF filter systems:

- Johnson Matthey/Eminox – CRT
- GAT – Eurofilter
- Cawdell – Purifilter
- Dinex – DiPEX (formerly Engelhard DPX)

A4.7 Active: fuel additives

The filter (wall- or full- flow) element of the system is similar to the passive particulate filter, the main difference being the source of regeneration for the trapped particulate. The abatement technology industry views fuel additives or fuel injection as the only viable options for an active regeneration strategy for a DPF-equipped HGV or bus/coach .

With active regeneration, the reliance on exhaust gas temperatures to regenerate the particulate filter is reduced and therefore these systems will work across a greater range of duty cycles, vehicle types and variety of operation. This is of particular benefit to off-road equipment (such as construction machinery) and on-road 'Inner City' applications where the duty cycle imposes a lot of stop-start operation. These conditions are found especially in smaller vehicles – eg below 7.5t, and refuse collection vehicles or road sweepers.

Metal based fuel additives, also called fuel soluble catalysts or fuel borne catalysts (FBC) are used in diesel filter systems to lower the particulate combustion temperature and to assist with regeneration. The most common additives include iron, copper, cerium and platinum. The mechanism of filter regeneration is similar to that of a catalysed diesel particulate filter (CDPF), except the use of an additive provides better contact between the catalyst and the trapped particulates. This is probably why additive regenerated filters 'burn off' at lower temperatures than catalysed ones.

Even though fuel additive filter systems may have lower regeneration temperatures, they may not always lend themselves to retro-fit applications, because of the need for some active control of the system – be it fuel dosing or other engine control strategies to ensure filter regeneration. At the simplest level, the dosing can be achieved by the operator adding the catalyst to the fuel directly when topping up the tank, or it can be undertaken automatically by a pump, adding the fuel catalyst in a fixed proportion to the fuel consumed. In this case, the system could be described as passive, rather than active. However, this system relies on the operator to monitor the additive level and fill up the tank when empty.

Since the year 2000, an increasing number of European passenger cars have been fitted with diesel particulate filters. Although the introduction of DPF for and during the Euro 4 stage are largely voluntary, it is expected that filters will be necessary to meet Euro 5 light duty emission standards. Such applications have a sophisticated dosing and regeneration strategy, supported by other engine management measures in order to periodically increase the exhaust gas temperature. They are not limited to fuel injection techniques, but also include optimisation of EGR, boost pressure, and other parameters – employing different techniques in different areas of the engine map.

Most of the light duty filter systems introduced in the early 2000's have used fuel additive regeneration, primarily to help avoid problems with sulphate PM emissions from sulphur in the fuel and to provide lower regeneration temperatures than catalysed filters. The drawbacks are the need to periodically replenish the additive and increased ash accumulation due to the additive residue. With the introduction of ultra-low sulphur diesel (50 ppm sulphur max from 2005 and 10ppm max sulphur from 2009), catalysed filters may start to become the preferred technology by manufacturers.

One further consequence of metallic fuel additives is that the metal is emitted from engine as metal oxide ash particles (nanoparticles). If large numbers of these small particulates are emitted, it is unlikely that this system could be used without a highly efficient wall- or full-flow filter to trap and oxidise them. It goes without saying that there is also an associated running cost with fuel additives.

Low Emission Certificate accredited fuel additive -regenerated filter systems:

- Clean Diesel Technology – Purifier e4
- Astra Vehicle Technology – Adastra DPF
- Eminox – FBC
- Pirelli Ambiente – Feelpure

A4.8 Active: electrical heating

The regeneration of any diesel particulate filter requires energy input to increase the temperature between the particulate matter accumulated in the filter and oxygen (and/or other oxidants) in the exhaust gas. This energy can be supplied to the exhaust gas, to the filter substrate, directly to the accumulated particulate, or through a combination. While being considered generally unsuitable for on-road applications (because there is normally insufficient on-board electrical power to regenerate the filter), electricity does offer flexibility for certain applications – such as construction plant and materials handling equipment whose operational cycles permit the required regeneration activities to be scheduled.

With substrate heating, the filter substrate is a conductor of electricity and serves as a resistive heater itself. Electrically heated filter substrates remain in the product development stage. Energy can be deposited directly to the particulate through the use of microwaves. The most common electric regeneration method involves heating of the exhaust gas or a stream of regeneration air by an electric resistive heater. This approach has been demonstrated in many programmes and commercialised in selected applications and can be used with a wide range of filter substrates. In systems utilising wall-flow monolith filters, the heater is usually placed upstream of the filter.

Electrically regenerated filters can be divided into three groups:

- **On-board regeneration.** The power needed for regeneration is drawn from the vehicle's electrical system. This is the only practical filter system concept applicable to on-road vehicles such as trucks and buses. The drawback of this approach is energy consumption and the significant extra load on the vehicle electrical system as well as a fuel consumption penalty. In order to minimise energy consumption, most on-board regeneration systems have a partial flow layout. With this system, only a portion of the exhaust gas stream is used for regeneration, while most of the exhaust flow bypasses the filter. If diesel particulate filtration is required all of the time, partial flow systems require dual filter units, so the flow can be switched between the filters for the filtration and regeneration modes.
- **Shore power regeneration.** Here the filter system is connected to an external power source, such as an electrical socket in a garage, for regeneration. Hence the vehicle is out of use for the duration of the regeneration cycle. Shore power regeneration systems are applicable to vehicle fleets with easy access to the source of external power (such as a fleet of construction vehicles operated within a construction site). This type of system would be impossible to use, or at least very inconvenient, on most road vehicles.
- **Off-board regeneration.** The particulate filter is removed from the vehicle and placed in an off-board unit for regeneration. If spare filters are available, a particulate laden filter can be quickly replaced with a regenerated one, thereby permitting much less downtime than it is the case in the shore power system. Shore power and off-board systems require regular maintenance and their operation depends on the intervention of the vehicle operator.

Low Emission Certificate accredited electrically-heated regenerated filter systems:

- Cawdell Group – Combifilter
- Per-Tec – PowerTrap

A4.9 DPF design, operational and service requirements

DPF devices have a range of criteria (eg exhaust gas space velocity, filter volume, temperature profiles, emission characteristics) which must be met in order for them to be effective and durable. Consequently these types of device have to be carefully matched to specific vehicle types and duty cycle. DPF abatement equipment may fail if used outside the specified boundaries, so manufacturers and suppliers are not always able to supply certain types or ages of vehicle or specific operational duties as the ability to support warranty claims may be compromised.

A host of operational considerations are taken into account when designing or specifying a DPF for a particular application. Some of the reasons why certain vehicles may not be able to employ DPF systems are:

- The need for ultra-low sulphur diesel fuel (less than 50ppm sulphur) is required for catalysed DPF and CRT systems;

- Light duty vehicles, or vehicles with a low duty cycle (eg extended idling times, frequent stop-starts) may not generate the required exhaust gas temperatures for regeneration;
- Worn and poorly maintained engines risk high oil consumption, increasing particulate build up and potentially plugging the filter. Euro I and pre-Euro vehicles are at greater risk and may not have the required emission characteristics (NO_X: PM ratio) for certain types of passive filters;
- Space constraints with specialist custom-built vehicles (or unique body configurations) may not have the physical space to install filters; and/or
- Long exhaust pipe runs result in lower exhaust temperatures at the filter face and could compromise regeneration (lagging may be an option).

The DPF system – whether passive or active – requires periodic maintenance. Ash build up in the filter from either the engine lubrication oil and/or fuel additives requires removal by cleaning, since this inorganic material does not burn off. Cleaning involves removal of accumulated ash with compressed air and specially designed equipment contains and collects the debris to avoid contamination of the workshop area. Filters have traditionally been turned round through 180° before being returned to their housings, but advances in cleaning techniques (and the fact that fine ash can still be 'blown' out of the filter into the atmosphere after cleaning and turning round) means that this is now happening less. Modern filters are designed so that they cannot be turned round in their housing after cleaning.

Most DPF abatement equipment suppliers will mandate the servicing of these filters as part of their warranty provision. Some suppliers will service the devices via a network of trained and approved fitters and depots, or large fleets may have in-house training and equipment supplied to carry out their own maintenance. The service intervals vary widely, depending on filter type, vehicle and engine type, duty cycle, and are normally based on a fixed mileage interval or are carried out when the back pressure monitor in the exhaust system signifies a high restriction indicative of a filter becoming blocked with ash and requiring cleaning.

Manufacturers of LEC-approved abatement equipment must supply an in-service warranty (to cover both technical performance & function and quality of manufacture & installation) for at least two years to provide full cover for parts, labour and on-site support costs.

A4.10 Particulate size distribution

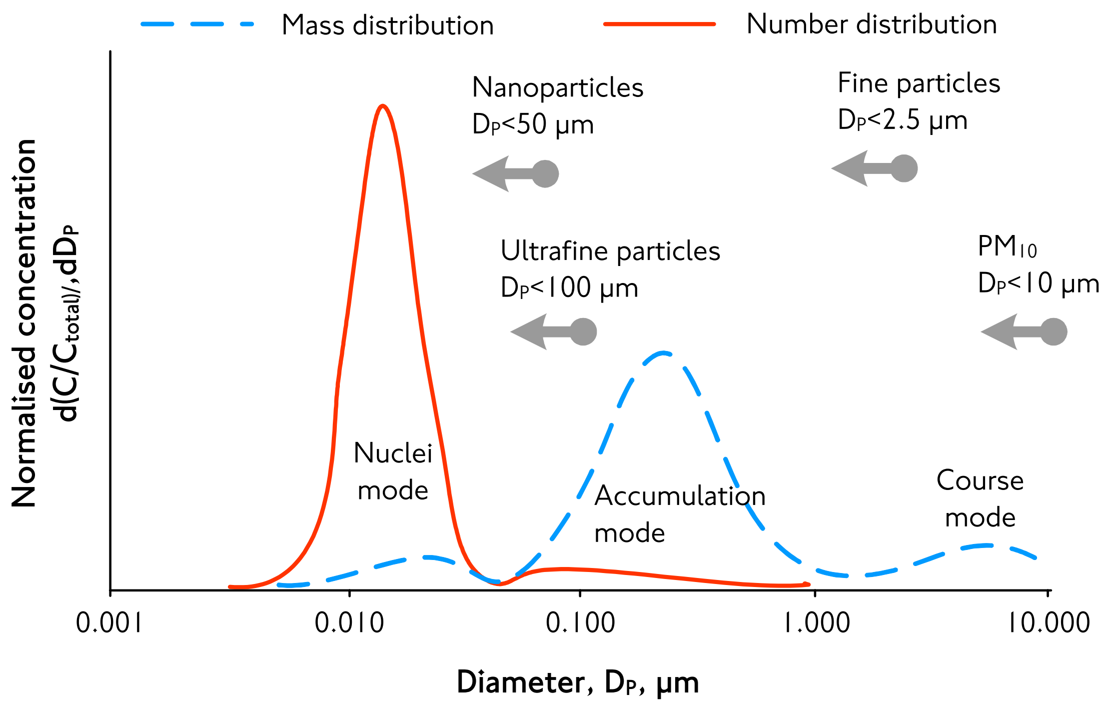
Particle size distributions from internal combustion engines (regardless of fuel type) have been receiving increased attention due to possible adverse health effects of fine and ultrafine particulates. Diesel emission control strategies, based on both engine design and after treatment, are being researched and evaluated for their effectiveness in the control of the finest fractions of diesel particulates and particle number emissions. The determination of particle sizes and numbers is much more sensitive to measuring techniques than the quantification of particulate mass emissions. Exhaust dilution ratio and sampling methods are key variables that must be taken into account to ensure accurate and repeatable results. Particle sizing instruments now have significantly better sensitivities than the gravimetric (mass) measurement, thereby allowing an alternative for the PM emission measurement in future engines, provided standardised measuring methods are developed and agreed internationally.

Ambient particulate matter is classified by most authors into the following categories based on their aerodynamic diameter (defined as the diameter of a 1 g cm^{-3} density sphere of the same settling velocity in air as the measured particle):

- PM_{10} – particulates of an aerodynamic diameter of less than 10 µm
- Fine particles – diameters below 2.5 µm
- Ultrafine particles – diameters below 0.1 µm or 100 nm
- Nanoparticles – characterised by diameters of less than 50 nm

A typical size distribution of diesel exhaust particulates is shown in Figure A4.5. Nearly all diesel particulates have sizes of significantly less than 1 µm and, as such, they represent a mixture of fine, ultrafine, and nanoparticles. Due to the current PM sampling techniques, diesel particulate matter includes both solids (such as elemental carbon and ash) and liquids (such as condensed hydrocarbons, water, and sulphuric acid). Formation of particulates starts with nucleation, which is followed by subsequent agglomeration of the nuclei particles. Nucleation occurs both in the combustion chamber (from solids) and in the dilution tunnel (from liquids) of the exhaust sampling system.

Figure A4.5 Diesel particulate size distribution.



Size distributions of diesel particulates have a well established 'bimodal' character which corresponds to the particle nucleation and agglomeration mechanisms. The associated particle types are referred to as the nuclei mode and the accumulation mode. Size distributions are usually presented using either particle mass or particle number weighted distribution curves, as shown above. Both the maximum particle concentration and the position of the nuclei and accumulation mode peaks depend on which representation is chosen. In mass distributions, the majority of the particulates are found in the accumulation mode, whereas in number distributions, most particles are found in the nuclei mode. Diesel particulate matter is therefore composed of a large number of small particles with very little mass, combined with relatively few larger particles which contain most of the total mass. A small fraction of diesel particulates reside in a third, coarse mode.